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UNC-SAM, A FORTRAN MONTE CARLO SYSTEM
FOR THE EVALUATION OF NEUTRON OR
GAMMA-RAY TRANSPORT IN
THREE-DIMENSIONAL GEOMETRY

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ABSTRACT

A code system (called UNC-SAM) which evaluates the transport of neutrons or gamma rays using Monte Carlo methods in complex three-dimensional geometry, has been written in FORTRAN for the Control Data Corporation 1604-A computer. The code will calculate fluxes, flux dependent functionals such as doses, and their standard deviations in geometry comprised of rectangular parallelepipeds which, in turn, may contain spheres, cylinders, parallelepipeds, or wedges.

In order to increase the efficiency of the Monte Carlo transport game, UNC-SAM uses an importance sampling technique. In addition, in the particular case of evaluating neutron fluxes in small volume detectors, a scoring by analytical estimation referred to as "flux at a point" is employed.

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1. INTRODUCTION

The United Nuclear Corporation Stochastic Approximation Method (UNC-SAM) is a code system in the FORTRAN language for evaluating the transport of neutrons or photons through matter by Monte Carlo techniques. It handles a three-dimensional geometry composed of rectangular parallelepipeds which, in turn, may contain spheres, cylinders, parallelepipeds, or wedges.

UNC-SAM represents the latest result of a continuing effort to develop complex geometry Monte Carlo programs of ever greater versatility and speed.* Most practical reactor and shield geometries can be handled by the geometry routines. Despite this, the geometry tracking portions of a problem consume considerably less than half the problem running time. In addition to high efficiency geometry routines, region and energy weighting and a special "flux-at-a-point" routine have been incorporated to reduce problem running time when fluxes are required at improbable regions of phase space.

Some applications in which UNC-SAM (or its predecessor ADONIS¹) have been used successfully are:

1. Transmission of neutrons through ducted shields
2. The analysis of experiments aimed at determining the production of gamma rays in shield materials by high energy neutrons

*Most of the numerical techniques employed in UNC-SAM were either formulated or invented by M. H. Kalos who guided the program throughout its development.

3. The transmission of neutrons and gamma rays through air, taking account of air and ground scattering
4. Investigation of shielding provided by proposed reactor containment structure
5. Measurement of shielding effectiveness of nested boxes containing geometrically complex devices
6. Weapon vulnerability studies.

The code system is written in FORTRAN for the Control Data Corporation's (CDC) 1604-A computer. A 32 K core and ≤ 6 magnetic tapes are required. UNC-SAM is in reality a chained series of independent programs which process cross-section and geometry data, do the transport problem, and edit the results. A brief summary of the independent programs contained in UNC-SAM follows. Fig. 1 indicates the information flow in the system.

GENDA

The Generation of Data routine (GENDA) starts with a fundamental set of neutron or photon cross-section data tabulated as a function of energy. It allows for the basic tabulation of the total cross section, the scattering cross section, the Legendre expansion coefficients of the differential scattering cross section, the inelastic scattering cross section for both level and continuum scattering, etc. These data are tabulated generally on differing energy meshes. GENDA processes the data to generate a set of cross-section data on a desired energy mesh. It includes the option of averaging with respect to a given weighting function, prescribed by input, if desired. Otherwise, it determines the desired cross-section set by either linear interpolation or by log-log interpolation. The spectrum of neutrons emitted by inelastic scattering, according to statistical theory, is used for heavier materials. For lighter materials, such as Li and Be, special treatments are available. The output of this routine is a tape which may be used as input to GENPRO.

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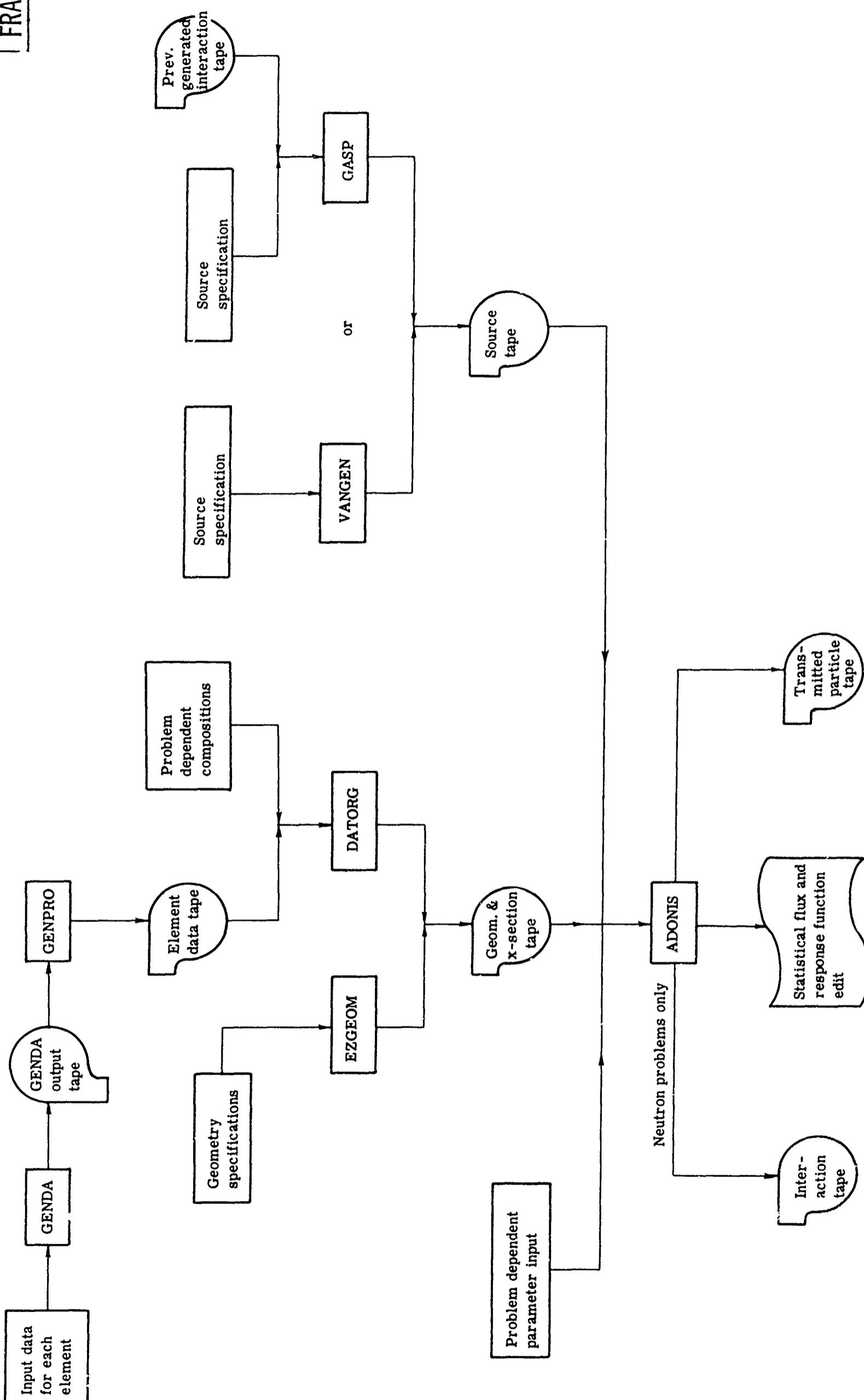


Fig. 1 — Macroscopic flow chart for UINC-SAM

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GENPRO

The GENDA Processor (GENPRO) routine uses the GENDA output to determine the tables of probabilities peculiar to a nuclide, required for a Monte Carlo code, at a prescribed energy mesh. For instance, the probability that a neutron suffers an elastic scattering is given by the ratio of elastic to total scattering at that energy. The probability of inelastic scattering from one energy to another is computed in this routine. At its conclusion, one has a library tape called the Element Data Tape (EDT), on a given energy mesh to be used in subsequent processing.

Up to this point, no problem oriented input was needed. The functioning of later routines (DATORG, EZGEOM, VANGEN, GASP) will be dependent on such problem oriented data.

DATORG

Given the concentrations of the materials comprising the configuration, an organized data tape, bearing the total macroscopic cross sections as well as other probabilities for mixtures of nuclides, is created by the DATORG routine. These are the problem-dependent cross-section data tabulated against energy at the prescribed energy mesh previously used in GENDA and GENPRO.

EZGEOM

This is a routine which takes a simplified geometrical description of the physical system, as provided by the problem originator, and produces the rather complex set of data required by the transport program ADONIS.

The problem originator must decompose space into a set of boxes known as "ordinary regions." Inside these boxes may be placed "nonordinary regions" consisting of spheres, cylinders, wedges, or other boxes. Nonordinary regions may enclose other nonordinary regions.

VANGEN

Source input corresponding to a primary neutron or gamma-ray problem is provided through the Volume Anisotropic Source Generator (VANGEN). VANGEN creates a source tape with the following types of distributions:

- P-(i) point source
- P-(ii) uniform plane source
- P-(iii) uniform volume source.

Corresponding to each of the above, a choice of angular distributions describing the source is available.

- A-(i) isotropic
- A-(ii) anisotropic according to a given (input) distribution
- A-(iii) monodirectional
- A-(iv) isotropic in the half plane.

Finally, to describe the energy variation of the source, these choices are available:

- E-(i) fission spectrum
- E-(ii) monoenergetic
- E-(iii) an arbitrary distributed energy source with equal probability steps prescribed by input.

The output of VANGEN is a tape for further processing.

GASP

The routine Gamma Source Particle generator (GASP) computes gamma-ray production from a primary neutron problem to serve as a source for a secondary gamma-ray problem. GASP requires:

1. An interaction tape (generated by a previous ADONIS problem) containing a record of all interactions able to cause gamma-ray emission

2. Probability numbers for each nuclide of the problem giving the probable number of gamma rays emitted as a function of energy
3. An angular distribution (as in VANGEN) for newly created gamma rays.

The routine can cope with the generation of other secondaries upon modification of the interaction tape input. The output of either GASP or VANGEN is a source particle tape which becomes input to ADONIS.

ADONIS

Given the appropriate output tapes of DATORG, EZGEOM, VANGEN, or GASP, and parametric input defining the problem to be solved, one is now ready to proceed with the neutron or gamma transport code (ADONIS). The program starts sets of 100 initial source particles from the source tape and processes these particles through all of their interactions and migrations, until death, reflection, transmission, or degradation below an energy cutoff occurs. As the particle travels, a variety of information is recorded, including:

1. An interaction tape for future secondary emission processing, or appropriate response function calculations relating to dose calculations, etc.
2. The total flux as a function of energy in each of the ordinary and non-ordinary geometric figures, along with its standard deviation
3. A transmitted particle tape for future processing.

Some of the Monte Carlo techniques employed in the ADONIS code are listed below.

1. Splitting or Russian roulette is performed at each geometric boundary crossed during the process of reaching a collision point. The splitting process is determined by the weights assigned to the regions on either side of the boundary. The weight of any region may vary with the neutron energy. Any additional particles generated by the splitting process are referred to as latent particles.

2. Fluxes in small detector regions are computed by the method referred to as flux-at-a-point. (At present this applies to neutron problems.)

Some of the output provided by ADONIS includes:

1. Number of absorptions, births, deaths, degradations
2. Flux and standard deviation per region energy bin
3. Dose and standard deviation per region.

SAM

SAM is the main program of an overlay tape containing the DATORG, EZGEOM, VANGEN, GASP and ADONIS programs. SAM functions as a program sequencer reading the title card of each set of input for a given problem calling the program required. It allows a user to place his input deck in any manner providing that, when a program appears in the sequence, all programs that provide input to that program have already been run.

The following sections of this report present a detailed discussion of the individual routines above. Where applicable, the physical principles underlying the program are discussed.

2. THE GENERATION OF DATA ROUTINE (GENDA)

Given experimental or theoretical microscopic cross-section data at arbitrary energies in a given range for elements of interest, it is often desirable to process these data into cross-section sets at specified energy point values.

The GENDA routine has been programmed in FORTRAN to accomplish this in the following manner:

1. The raw cross-section data are tabulated according to an established format which can be easily modified and updated. The point values of the input cross-section data are selected to give the best detailed representation of the cross-section variation with energy for the interpolation technique used.
2. For a given element and type of cross section, intermediate point values are obtained from these tables, using either linear or log-log interpolation techniques as directed by the input.
3. Weighted point values of cross sections in a specified energy mesh may be evaluated using a given weighting function. This input function is tabulated in a similar manner as the raw cross-section data and intermediate point values are obtained by interpolation.

2.1 TECHNICAL DESCRIPTION

Let $\sigma(E)$ denote generically a typical cross section at energy E . This might stand for the total cross section, the scattering cross section, the Legendre expansion coefficient (f_p) of the differential scattering cross section, the inelastic scattering cross section for level or continuum scattering, etc. (the cross-section types included appear in the input instructions). Let $\sigma_0(E)$ be the continuous portion of the typical cross section $\sigma(E)$. On occasion, where many resonances exist, a set of resonance parameters $A_\nu(E_\nu)$ may be given for each generic cross section type such that for the purpose of suitable averages, $\sigma(E)$ is representable as:

$$\sigma(E) = \sigma_0(E) + \sum_{\nu=1}^{\nu_{\max}} A_\nu(E_\nu) \delta(E-E_\nu) \quad (1)$$

where $\delta(E-E_\nu)$ is the Dirac delta function of argument $E-E_\nu$. This characterization of $\sigma(E)$ is allowed only when the cross-section averaging routine (CAR) is used; otherwise, an infinitely narrow resonance peak is not physically reasonable, nor computationally manageable.

Let E_j^G , $j = 1, 2, \dots, J$ be a set of final energies in decreasing order at which the output data are to be tabulated. These may be tabulated either as input or computed given the highest energy, E_{\max} , the number of final energies, J , and the constant lethargy spacing, h , such that

$$h = \frac{1}{J} \ln \frac{E_{\max}}{E_J} \quad (2)$$

where E_J is the lowest energy.

Let $\phi(E)$ be an arbitrary weighting function supplied by an input table

$$\phi(E) = \phi_0(E) + \sum_{\tau=1}^{\tau_{\max}} B_\tau(E_\tau) \delta(E-E_\tau). \quad (3)$$

(The E_T must not have an energy value equal to any of the E_ν .) Let $\sigma_0(E)$ and $\phi_0(E)$ be given as functions of energy such that between tabulated values these functions are either linear or exponential.

The GENDA code then provides for the following mutually exclusive options.

1. Find $\sigma(E_j^G)$; $j = 1, \dots, J_{\max}$ by linear interpolation
2. Find $\sigma(E_j^G)$; $j = 1, \dots, J_{\max}$ by log-log interpolation
3. Find $\sigma(E_j^G)$; $j = 2, \dots, J-1$ by

$$\sigma(E_j^G) = \frac{\int_{(E_j^G + E_{j+1}^G)/2}^{(E_j^G + E_{j-1}^G)/2} \sigma_0(E) \phi_0(E) dE + \sum A_\nu(E_\nu) \phi_0(E_\nu) + \sum B_T(E_T) \sigma_0(E_T)}{\int_{(E_j^G + E_{j+1}^G)/2}^{(E_j^G + E_{j-1}^G)/2} \phi_0(E) dE + \sum B_T(E_T)}$$

(4)

where the sums include those values of E_ν and E_T falling within the integration interval.

For the purpose of CAR, the energy mesh used is made up of the set of all energies at which σ and ϕ are given, plus the end points of the interval of integration. In the present program, the integration is carried out numerically, using the trapezoidal rule. Consequently, the richer the input mesh, the better the results. It should be noted that exact integration could be performed at the price of some modifications of the program.

The cross section at thermal energy may be included in GENDA. In that case, the lowest entry in the final energy mesh tabulation is the thermal energy.

In addition, GENDA can compute the synthesized differential scattering cross section

$$\sigma(E_j^G, \omega) = \frac{\sigma_n(E_j^G)}{4\pi} \sum_{\ell=0}^L (2\ell+1) f_\ell(E_j^G) P_\ell(\omega) \quad \text{for } \omega = -1 (0.01) 1 \quad (5)$$

where σ_n = the elastic scattering cross section

$P_\ell(\omega)$ = the Legendre polynomial of order ℓ evaluated at the angle cosine ω

$f_\ell(E_j^G)$ = the Legendre expansion coefficient.

All negative values for $\sigma(E_j^G, \omega)$ are printed out. An edit on the coarser mesh -1 (0.1) 1 is also available.

For the treatment of inelastic scattering, it is necessary to describe in greater detail the kernel $g(E_j^G, E')$ which represents the probability that, following an inelastic scattering, a neutron at energy E_j^G will scatter into energy E' . The spacing of the discrete energy levels in the nucleus is known to decrease with increasing energy. At high energies, the levels are so close that they may be considered as a continuum of energy levels. Let E_{BC} be the energy at which the discrete level spectrum can be considered to pass over into a continuous spectrum. Then, for incident neutron energies less than or equal to E_{BC} , only discrete level inelastic scattering occurs. The kernel $g(E_j^G, E')$ is representable as a sum of delta functions

$$g(E_j^G, E') = g_D(E_j^G, E') = \sum_{\text{all } \nu} a_\nu(E_j^G) \delta[E_j^G - (E' + E^\nu)] \quad E^\nu < E_j^G \leq E_{BC} \quad (6)$$

where ν = the ν^{th} energy level

E^ν = the energy of the ν^{th} discrete level

$a_\nu(E_j^G)$ = the probability that a neutron at energy E_j^G will scatter into energy $E' = E_j^G - E^\nu$.

From the definition of g_D it follows that

$$\int_0^{E_j^G} g_D(E_j^G, E') dE' = \sum_{\text{all } \nu} a_\nu(E_j^G) = 1 \quad (7)$$

for $E_j^G \geq E'$. If $E_j^G < E'$, the inelastic scattering cross section is zero and $g_D(E_j^G, E')$ is undefined.

If the incident neutron energy is greater than E_{BC} , two cases must be considered.

1. If E_j^G is sufficiently large that the probability of discrete level scattering is zero, then only continuum level scattering occurs. Let E_{BD} be the energy above which all a_ν are zero, then the kernel $g(E_j^G, E')$ can be represented by a continuous probability distribution function, $g_c(E_j^G, E')$ which satisfies the following condition.

$$\int_0^{E_j^G} g_c(E_j^G, E') dE' = 1 \quad (8)$$

2. If $E_{BC} < E_j^G \leq E_{BD}$, then both continuum and discrete level scattering occur. Both the continuum and discrete kernels, g_c and a_ν 's are computed, satisfying the normalization given by Eqs. 7 and 8. Hence, the inelastic scattering kernel is

$$g(E_j^G, E') = \frac{\sigma_{nn',c}(E_j^G) g_c(E_j^G, E') + \sigma_{nn',D}(E_j^G) g_D(E_j^G, E')}{\sigma_{nn',c}(E_j^G) + \sigma_{nn',D}(E_j^G)} \quad (9)$$

where $\sigma_{nn',c}$ and $\sigma_{nn',D}$ are the cross sections for the excitation of the continuum and of the discrete levels, respectively.

The continuum energy spectrum of neutrons emitted per inelastic scattering at energy E is obtained using a routine called ASPIC which computes the probability $g(E, E')$ according to a statistical theory.*

$$g^{(i)}(E, E') = \frac{\int_0^E E' \sigma_C^{(i)}(E') \rho^{(i)}(E-E') dE'}{\int_0^E E' \sigma_C^{(i)}(E') \rho^{(i)}(E-E') dE'} \quad (10)$$

where $\sigma_C^{(i)}(E)$ is the cross section for compound nucleus formation and $\rho^{(i)}(E)$ is the level density in the nucleus i ($i=1$ refers to the target nucleus).

The following form is assumed for the level density:

$$\begin{aligned} \rho^{(i)}(E) &= 0 && \text{for } E < E_1^{(i)} \\ \rho^{(i)}(E) &= \rho_0 && \text{for } E_1^{(i)} < E < E_0^{(i)} \\ \rho^{(i)}(E) &= \rho_0 \exp [2\sqrt{a^{(i)}_1} E - 2\sqrt{a^{(i)}_1 E_0^{(i)}}] && \text{for } E > E_0^{(i)}. \end{aligned} \quad (11)$$

For the treatment of $(n, 2n)$ reactions, it is assumed that the first neutron has the distribution (Eq. 10) where $i = 1$. After the emission of the first neutron, the target nucleus is left at excited states E^+ with a population density:

$$R(E, E^+) = g^{(i)}(E, E-E^+). \quad (12)$$

$R(E^+)$ has a maximum at $E^+ = E - \sqrt{E/a^{(1)}}$ [$\sqrt{E/a^{(1)}}$ is the nuclear temperature]. We make the simplifying assumption that all secondary neutrons are emitted from the states $E^+ = E - \sqrt{E/a^{(1)}}$. Applying statistical theory, the spectrum of secondary neutrons per $(n, 2n)$ collision is given by

$$g^{(2)}[E - \sqrt{E/a^{(1)}} - E_t, E'] \quad (13)$$

*See terminology and definitions at the end of this section.

where E_t is the threshold for the $(n,2n)$ reaction, $g^{(2)}$ is given by Eq. 10, and the superscript (2) refers to the nucleus left after the $(n,2n)$ reaction on the target.

In order to account for the neutrons leading to the ground state of this final nucleus, one should set $E_t^{(2)} \approx 0$ [choose $E_t^{(2)} = 0.01$]. Hence, the composite spectrum of neutrons emitted per $(nn'; n,2n)$ reaction is given by

$$g(E, E') = g^{(1)}(E, E') + \frac{\sigma_{n,2n}(E)}{\sigma_{nn',c}(E)} g^{(2)}(E, E') \quad (14)$$

where $\sigma_{n,2n}(E)$ is included into $\sigma_{nn',c}(E)$ in GENDA.

In the event that the core storage requires more than 18,000 words for $g(E, E')$, the code determines a lowest value for E' (which will be higher than the lowest energy of the problem) so that $g(E, E')$ fits in storage. The portion of $g(E, E')$ neglected is generally negligible.

The above description of the calculation of the probability $g(E, E')$ is not adequate for light nuclei. Special treatments for lithium and beryllium are available at the user's option.

The GENDA Li option² (see Fig. 2) assumes a continuous spectrum for $E_j^G \geq 3.95$ Mev. For E below 3.95 Mev, the inelastic scattering arises only from the excitation of the 0.477-Mev level.

The continuous probability distribution function, $g_c(E, E')$, is taken as constant with a value of $1/E_{\max}$ where

$$E_{\max} = 1.040 E_j^G - 4.100 \quad (15)$$

and stretches from $E' = 2 \times 10^{-6}$ Mev to an E'_j such that $E'_{j+1} \geq E_{\max} \geq E'_j$ where E'_j and E'_{j+1} are adjacent energies in the integration mesh. It should

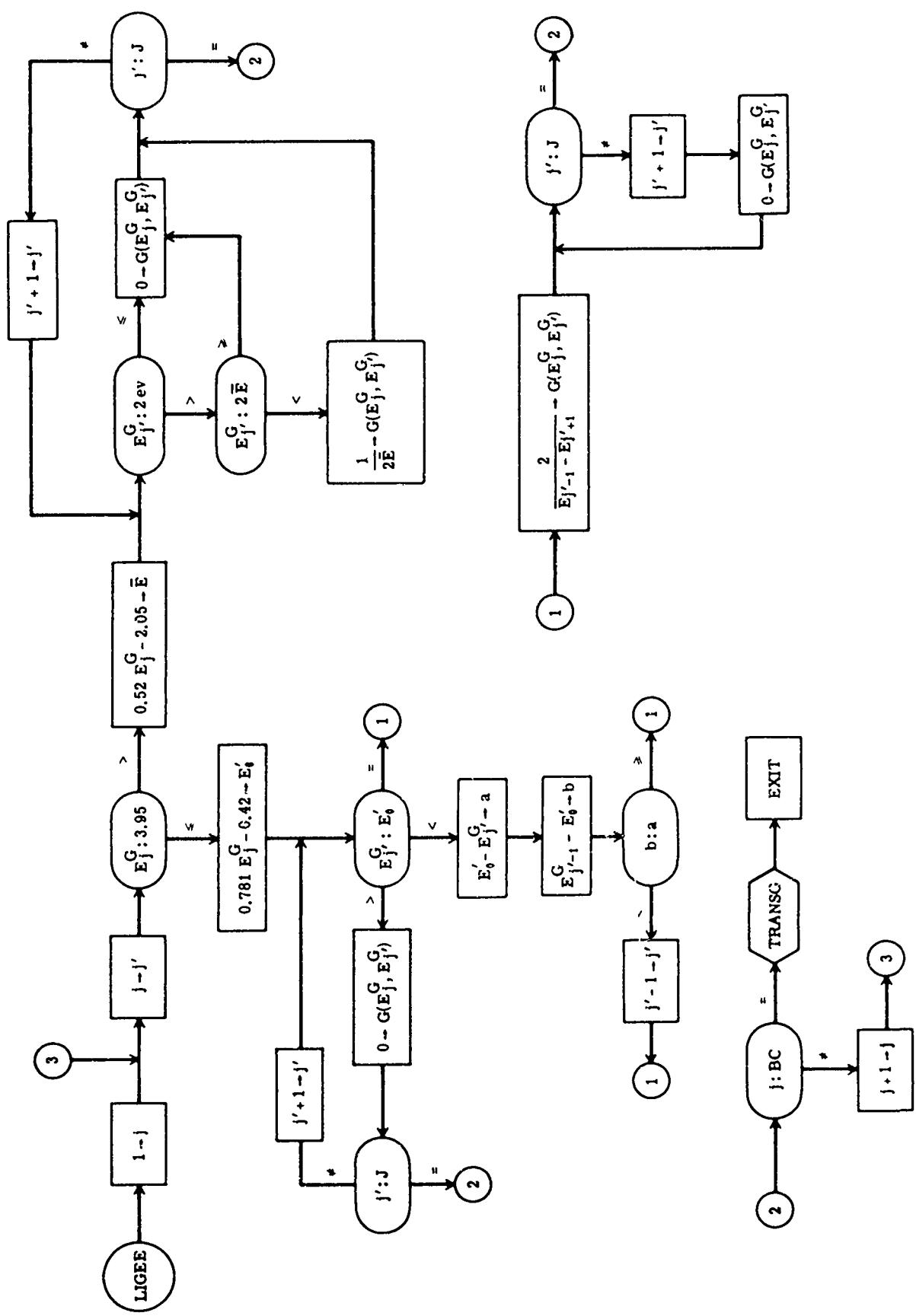


Fig. 2 -- Lithium $g(E, E')$ computation

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be noted that

$$\int g_C(E, E') dE' = \frac{E'_{j+1} + E'_j}{2 E_{\max}} \quad (16)$$

is not equal to 1, though close to it. Because of the Li nucleus recoil, $g_D(E, E')$ is obtained as follows:

$$g_D(E, E') = \frac{2 \delta (E' - E'_j)}{E'_{j+1} - E'_{j-1}} \quad (17)$$

where for each E the value of E'_j is selected which lies closest to

$$E'_0 = 0.78i E - 0.420 \text{ Mev} \quad (18)$$

The GENDA Be option³ (see Fig. 3) uses revised data as obtained by Goldstein and Mechanic.⁴

Briefly,

1. For $E_j^G < 2 \text{ Mev}$:

$$g(E_j^G, E') = 0$$

2. For $2 \text{ Mev} \leq E_j^G \leq 2.83 \text{ Mev}$:

Of the two types of neutrons emitted, $\epsilon(E_j^G)$ go via excitation of the 2.43-Mev level of Be^9 . The remaining $2 - \epsilon$ neutrons are emitted with a constant distribution stretching from zero to the highest energy allowed (namely $E = 1.7$).

$$g_C(E_j^G, E') = \frac{2 - \epsilon(E_j^G)}{E_j^G - 1.7} \quad (19)$$

3. For $E_j^G \geq 2.83 \text{ Mev}$:

The contribution from the discrete level must be added. Thus, the overall distribution $g(E_j^G, E')$ becomes

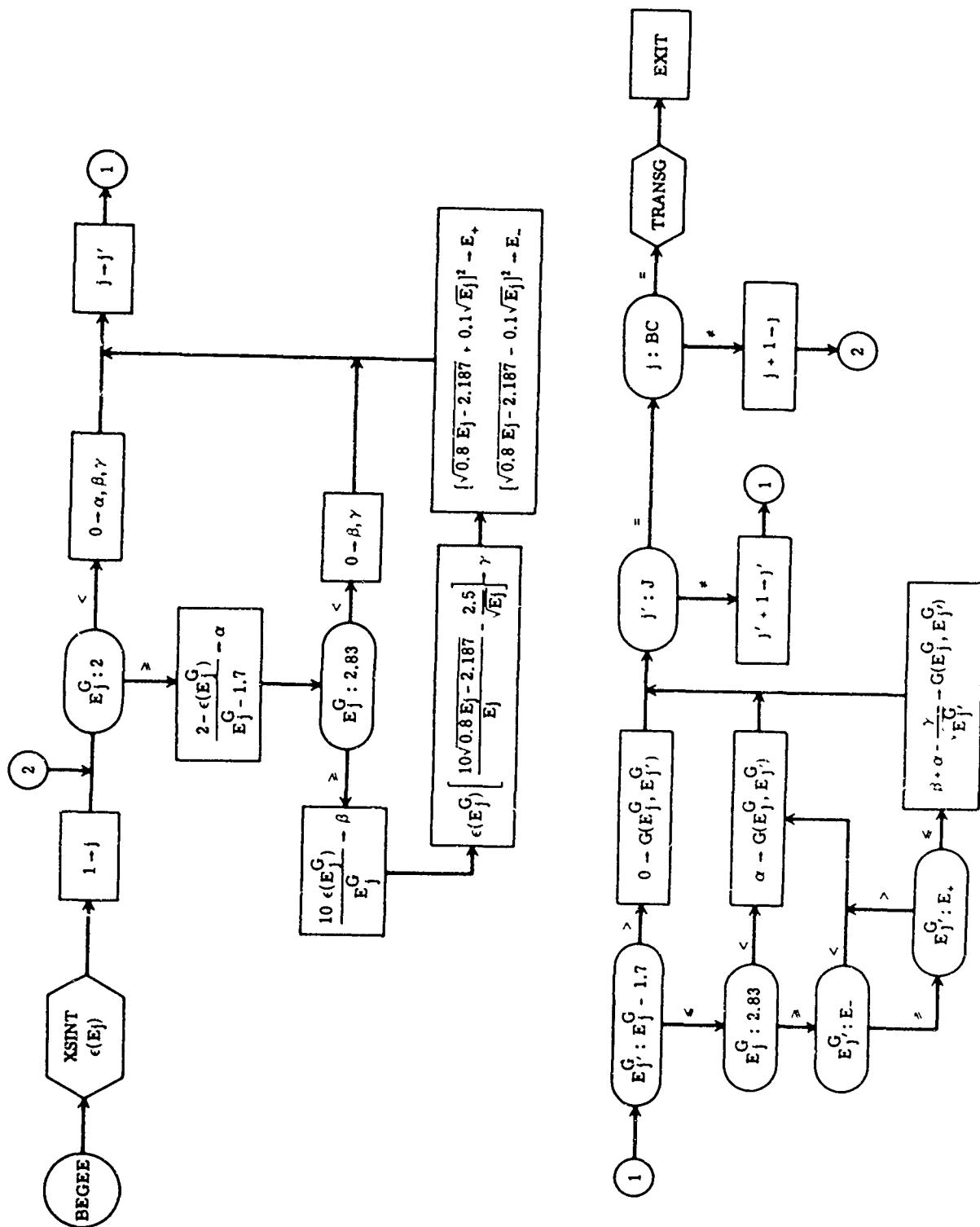


Fig. 3 - Beryllium $g(E, E')$ computation

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$$g(E_j^G, E') = g_c(E_j^G, E') + \epsilon(E_j^G) \left[\frac{10}{E_j^G} - \frac{1}{\sqrt{E'}} \left(\frac{10\sqrt{0.8 E_1^G - 2.187}}{E_j^G} - \frac{2.5}{\sqrt{E'}} \right) \right] \quad (20)$$

$\epsilon(E_j^G)$ is taken from the data compiled by Lustig and Kalos.⁵

Terminology for Section 2.1

E_t	the threshold of the (n,2n) reaction
$a^{(1)}, E_0^{(1)}$	level density parameters for the target nucleus
$a^{(2)}, E_0^{(2)}$	level density parameters for the nucleus
$E_1^{(1)}$	energy at which the continuum starts
$E_1^{(2)}$	should be set equal to 0.01
$\sigma_c^{(1)}$	cross section for compound nucleus formation of the target nucleus
$\sigma_c^{(2)}$	cross section for compound nucleus left over after the (n,2n) reaction.

2.2 THE PREPARATION OF INPUT DATA FOR GENDA

Unless otherwise stated, all data for this code are in standard FORTRAN E format. The data are punched in six fields of 10 columns each (i.e., 6E10.4). For the general data decks, it is in the order of energy followed by its cross section.

Example

Column

1-10	E_1
11-20	$\sigma(E_1)$
21-30	E_2
31-40	$\sigma(E_2)$
41-50	E_3
51-60	$\sigma(E_3)$

	10	20	30	40	50	60
E_1	$\sigma(E_1)$	E_2	$\sigma(E_2)$	E_3	$\sigma(E_3)$	

All energies must span the range from E_{\max} to $E_{J \max}^G$ (the minimum energy) with the exception of the discrete inelastic scattering cross section ($\sigma_{nn',L}$).

The data control information is in integer format, with the exception of the true mass number which is in F format.

2.3 GENDA PROBLEM INPUT

2.3.1 Title Card

Any 80 Hollerith characters (e.g., user's name, element name, date, etc.)

2.3.2 Problem Control Card

Column	Item
1-3	Number of elements (NEL)
4-7	Number of final energies (JMAX) (<450)
8	IEN = 0 - compute final energy table with fixed lethargy IEN = 1 - final energy table is input
9	IPHI = 0 - weighting function $\phi_c(E)$ is not present IPHI = 1 - weighting function $\phi_c(E)$ is present
10	IDELP = 0 - table of $B_\gamma(E_\gamma)$ is not present IDELP = 1 - table of $B_\gamma(E_\gamma)$ is present

Note:

IDELP must = 0 if IPHI = 0.

2.3.3 Energy Input

For IEN = 0

Column	Item	
1-10	E_{MAX} - maximum energy (Mev)	Floating
11-20	H, fixed lethargy step	Floating
	$\frac{1}{JMAX} \ln \frac{E_{MAX}}{E_{JMAX}}$	

For IEN = 1

Energy table E_j^G , $j = 1, 2, \dots, JMAX$; $E_j^G > E_{j+1}^G$
Format (6E10.4)

2.3.4 Weighting Function $\phi_c(E)$ (IPHI = 1)

Identification Card

Column	Item
1-6	Any six Hollerith characters for identification
8	= 1 - linear
	= 2 - linear on log-log paper
9-12	Number of $\phi_c(E)$ tabulated (≤ 300)

$E^\phi, \phi_c(E^\phi)$ Data Deck

Note:

The $\phi_c(E^\phi)$ must be included if CAR type group averaging is to be used.

2.3.5 Weighting Function $B_T(E_T)$ (IPHI = 1 and IDELP = 1)

Identification Card

Column	Item
1-6	Any six Hollerith characters
7-8	Number of B_T tabulated (≤ 99 entries)

$E_T, B_T(E_T)$ Data Deck

2.4 GENDA ELEMENT INPUT

2.4.1 Element Control Card

Column	Item
1-6	Element name, Hollerith format
7-13	True mass (F format)
14-23	Integral mass (numerical identification) integer.
DDDDZZZEEE	D - field for data
14 23	Z - field for atomic number E - field for element identification E = 000 if natural element
24-50	Control for the following Data = 1 - data are present Data = 0 - data are not present
24	Blank
25	Total cross section, σ_T
26	Elastic scattering cross section, σ_n
27, 28	The order of expansion ($T^N \leq 20$, f_p , $p = 1, 2, \dots, T^N$) if the elastic scattering is anisotropic
29	Excitation of discrete levels, $\sigma_{nn',L}$
30, 31	The order of expansion (T^L) if the excitation of discrete levels is anisotropic
32	Excitation of the continuum, $\sigma_{nn',C}$ (includes $\sigma_{n,2n}$)
33, 34	The order of expansion (T^C) if the excitation of the continuum is anisotropic
35	Cross section for the emission of two neutrons $\sigma_{n,2n}$
36	Fission cross section, σ_f
37	Absorption cross section, $\sigma_{\alpha,ss}$
38	Transport cross section, σ_{tr}
39	Cross section for the emission of an α particle σ_α
40	Cross section for the emission of a proton, σ_p
41	Cross section for the emission of H_2 , σ_{H_2}
42	Cross section for the emission of H_3 , σ_{H_3}
43	Radiative capture cross section, $\sigma_{n,\gamma}$
44	Fission γ spectra
45	Absorption γ spectra
46	Nonelastic γ spectra
47	$\nu(E)$ data
48	$\eta(E)$ data
49	Edit synthesized f_p data
50	Thermal data

2.4.2 Total Cross Section, σ_T

Identification Card

Column	Item
1-6	Any six Hollerith characters
7	= 1 - linear
	= 2 - linear on log-log paper
10	= 0 - $\sigma(E_i^G)$ found by interpolation
	= 1 - $\sigma(E_j^G)$ found by CAR type averaging
11-14	Number of $\sigma(E)$ tabulated (≤ 1100)
15	= 0 - no resonance parameters
	= 1 - resonance parameters, A_ν for σ_T

E, $\sigma_T(E)$ Data Deck

Thermal Value of σ_T (Format E10.4)

Identification Card for A_ν

Column	Item
1-6	Any six Hollerith characters
7-8	Number of A_ν tabulated (≤ 99)

$E_\nu, A_\nu(E_\nu)$ Data Deck

2.4.3 Elastic Scattering Cross Section, σ_n

Identification Card

Column	Item
1-6	Any six Hollerith characters
7	= 1 - linear
	= 2 - linear on log-log paper
10	= 0 - $\sigma(E_j^G)$ found by interpolation
	= 1 - $\sigma(E_i^G)$ found by CAR type averaging
11-14	Number of $\sigma(E)$ tabulated (≤ 1100)
15	= 0 - no resonance parameters
	= 1 - resonance parameters, A_ν for σ_n

$E, \sigma_n(E)$ Data Deck

Thermal Value for σ_n (Format E10.4)

Identification Card for A_ν

Column	Item
1-6	Any six Hollerith characters
7-8	Number of A_ν tabulated (≤ 99)

$E_\nu, A_\nu(E_\nu)$ Data Deck

2.4.4 Angular Distribution Data, f_p

Anisotropic elastic scattering for each f_p , $p = 1, 2, \dots, T^N$ ($T^N \leq 20$).

Identification Card (one for each f_p data deck)

Column	Item
1-6	Any six Hollerith characters
7	= 1 - linear
	= 2 - linear on log-log paper
10	= 0 - $f_p(E)$ found by interpolation
	= 1 - $f_p(E)$ found by CAR type averaging
11-14	Number of $f_p(E)$ tabulated (≤ 1100)

2.4.5 Inelastic Scattering Data, Discrete, $\sigma_{nn',L}$

Inelastic Scattering Data, Discrete, Control Card

Column	Item
1-10	E_{BD} , energy at which the discrete spectrum begins. This value can be less than E_{MAX} (e.g., $E_{MAX} = 18.01739$ Mev, $E_{BD} = 7.93$ Mev)
11-13	NU, number of level parameter, $a_\nu \sigma_{nn',L}$ (< 20)

Excitations of Discrete Levels, $\sigma_{nn',L}$

Identification Card

Column	Item
1-6	Any six Hollerith characters
7	= 1 - linear
	= 2 - linear on log-log paper
10	= 0 - $\sigma(E_j^G)$ found by interpolation
	= 1 - $\sigma(E_j^G)$ found by CAR type averaging
11-14	Number of $\sigma(E)$ tabulated (≤ 1100)
15	= 0 - no resonance parameters
	= 1 - resonance parameters, A_ν , for $\sigma_{nn',L}$

$E, \sigma_{nn',L}(E)$ Data Deck from E_{BD} to E_j^G MAX

Thermal Value of $\sigma_{nn',L}$ (Format E10.4)

Identification Card for A_ν

Column	Item
1-6	Any six Hollerith characters
7-8	Number of A_ν tabulated (≤ 99)

$E_\nu, A_\nu(E_\nu)$ Data Deck

E_ν Deck

$\nu = 1, 2, \dots, NU \quad E_1 < E_2 < \dots < E_{NU}$ (format 6E10.4)

Level Parameters $a_\nu \sigma_{nn',L}$

Identification Card (one for each deck of $A_\nu \sigma_{nn',L}$, as $\nu = 1, 2, \dots, NU$)

Column	Item
1-6	Any six Hollerith characters
7	= 1 - linear
	= 2 - linear on log-log paper

Column	Item
10	= 0 - $a_{\nu} \sigma_{nn',L}(E_j^G)$ found by interpolation = 1 - $a_{\nu} \sigma_{nn',L}(E_j^G)$ found by CAR type averaging
11-14	Number of $a_{\nu} \sigma_{nn',L}$ tabulated (≤ 1100)

$E, a_{\nu} \sigma_{nn',L}(E)$ Data Deck from E_{BD} to E_j^G MAX

Thermal Value of $a_{\nu} \sigma_{nn',L}$ (Format E10.4)

Identification Card for A_{ν}

Column	Item
1-6	Any six Hollerith characters
7-8	Number of A_{ν} tabulated (≤ 99)

$E_{\nu}, A_{\nu}(E_{\nu})$ Data Deck

Anisotropic $\sigma_{nn',L}$

The routines to handle this cross section have not been programmed.

2.4.6 Excitation of the Continuum, $\sigma_{nn',c}$ (Includes $\sigma_{n,zn}$)

Inelastic Scattering Data, Continuous, Control Card

Column	Item
1-10	E_{BC}
13	IGOP: Option to commute $G(E, E')$ IGOP = 1 - ASPIC IGOP = 2 - lithium special code IGOP = 3 - beryllium special code

Excitation of the Continuum, $\sigma_{nn',c}$

Identification Card

Column	Item
1-6	Any six Hollerith characters
7	= 1 - linear
	= 2 - linear on log-log paper
10	= 0 - $\sigma(E)$ found by interpolation
	= 1 - $\sigma(E)$ found by CAR type group averaging
11-14	Number of $\sigma(E)$ tabulated (≤ 1100)
15	= 0 - no resonance parameters
	= 1 - resonance parameters, A_ν for $\sigma_{nn',c}$

$E, \sigma_{nn',c}(E)$ Data Deck ($E_{MAX} = E_{MIN}$)

Thermal Value of $\sigma_{nn',c}$ (Format E10.4)

Identification Card for A_ν

Column	Item
1-6	Any six Hollerith characters
7-8	Number of A_ν tabulated (≤ 99)

$E_\nu, A_\nu(E_\nu)$ Data Deck

IGOP = 1

Parameters for the Temperature Model of the Nucleus

Column	Item
1-10	E_t , the threshold energy of the $(n,2n)$ reaction
11-20	$a^{(1)}$ - level density parameter for the target nucleus
21-30	$a^{(2)}$ - level density parameter for the nucleus after an $(n,2n)$ reaction
31-40	$E_1^{(1)}$ - level density parameter for the target nucleus
41-50	$E_1^{(2)}$ - level density parameter for the nucleus after an $(n,2n)$ reaction
51-60	$E_1^{(1)}$ - first excited state
61-70	$E_1^{(2)}$ - should be set equal to 0.0

Cross Section for the Emission of Two Neutrons, $\sigma_{n,2n}$

1. Identification Card

Column	Item
1-6	Any six Hollerith characters
7	= 1 - linear
	= 2 - linear on log-log paper
10	= 0 - $\sigma(E_i^G)$ found by interpolation
	= 1 - $\sigma(E_j^G)$ found by CAR type group averaging
11-14	Number of $\sigma(E)$ tabulated (≤ 1100)
15	= 0 - no resonance parameters
	= 1 - resonance parameters, A_ν for $\sigma_{n,2n}$

2. $E, \sigma_{n,2n}(E)$ Data Deck

3. Thermal Value of $\sigma_{n,2n}$ (Format E10.4)

4. Identification Card for A_ν

Column	Item
1-6	Any six Hollerith characters
7-8	Number of A_ν tabulated (≤ 99)

5. $E_\nu, A_\nu(E_\nu)$ Data Deck

Cross Section for Compound Nucleus Formation of the Target Nucleus, $\sigma_c^{(1)}$

1. Identification Card

Column	Item
1-6	Any six Hollerith characters
7	= 1 - 'inear
	= 2 - linear on log-log paper
10	= 0 - $\sigma(E_i^G)$ found by interpolation
	= 1 - $\sigma(E_j^G)$ found by CAR type group averaging
11-14	Number of $\sigma(E)$ tabulated (≤ 1100)

2. $E, \sigma_c^{(1)}(E)$ Data Deck

Cross Section for Compound Nucleus Left Over After the (n,2n) Reaction, $\sigma_c^{(2)}$

1. Identification Card

Column	Item
1-6	Any six Hollerith characters
7	= 1 - linear
	= 2 - linear on log-log paper
10	= 0 - $\sigma(E_j^G)$ found by interpolation
	= 1 - $\sigma(E_j^G)$ found by CAR type group averaging
11-14	Number of $\sigma(E)$ tabulated (≤ 1100)

2. $E, \sigma_c^{(2)}(E)$ Data Deck

IGOP = 2 (Lithium Special Code)

No input required.

IGOP = 3 (Beryllium Special Code)

Identification Card

Column	Item
1-6	Any six Hollerith characters
7	= 1 - linear
	= 2 - linear on log-log paper
10	= 0 - $\epsilon(E_j^G)$ found by interpolation
	= 1 - $\epsilon(E_j^G)$ found by CAR type group averaging
11-14	Number of $\epsilon(E)$ tabulated (≤ 1100)

$E, \epsilon(E)$ Data Deck

Anisotropic $\sigma_{nn',c}$

The routines to handle this cross section have not been programmed.

2.4.7 Cross Section for the Emission of Two Neutrons, $\sigma_{n,2n}$

(If $\sigma_{n,2n}$ has been supplied for the ASPIC routine do not input again and do not flag $\sigma_{n,2n}$ on the element control card.)

Identification Card

Column	Item
1-6	Any six Hollerith characters
7	= 1 - linear
	= 2 - linear on log-log paper
10	= 0 - $\sigma(E_j^G)$ found by interpolation
	= 1 - $\sigma(E_j^G)$ found by CAR type group averaging
11-14	Number of $\sigma(E)$ tabulated (≤ 1100)
15	= 0 - no resonance parameters
	= 1 - resonance parameters, A_ν for $\sigma_{n,2n}$

$E, \sigma_{n,2n}(E)$ Data Deck

Thermal Value of $\sigma_{n,2n}$ (Format E10.4)

Identification Card for A_ν

Column	Item
1-6	Any six Hollerith characters
7-8	Number of A_ν tabulated (≤ 99)

$E_\nu, A_\nu(E_\nu)$ Data Deck

For the following eight cross sections (see Section 2.4.8) the following general format is to be used in the order of the cross sections listed.

Identification Card

Column	Item
1-6	Any six Hollerith characters
7	= 1 - linear
	= 2 - linear on log-log paper

10	= 0 - $\sigma(E_j^G)$ found by interpolation
	= 1 - $\sigma(E_j^G)$ found by CAR type group averaging
11-14	Number of $\sigma(E)$ tabulated (≤ 1100)
15	= 0 - no resonance parameters
	= 1 - resonance parameters, A_ν for σ

E, $\sigma(E)$ Data Deck

Thermal Value of σ (Format E10.4)

Identification Card for A_ν

Column	Item
1-6	Any six Hollerith characters
7-8	Number of A_ν tabulated (≤ 99)

$E_\nu, A_\nu(E_\nu)$ Data Deck

2.4.8 Other Cross Sections

1. Fission Cross Section, σ_f
2. Absorption Cross Section, σ_{abs}
3. Transport Cross Section, σ_{tr}
4. Cross Section for the Emission of an α Particle, σ_α
5. Cross Section for the Emission of a Proton, σ_p
6. Cross Section for the Emission of H_2 , σ_{H_2}
7. Cross Section for the Emission of H_3 , σ_{H_3}
8. Radiative Capture Cross Section, $\sigma_{n,\gamma}$

The routines to handle fission γ spectra, absorption γ spectra, nonelastic γ spectra, $\nu(E)$ data, and $\eta(E)$ data have not been programmed.

If the program control card specifies more than one element, repeat Section 2.4 of the above input preparation for each element.

2.5 GENDA OUTPUT

The GENDA output consists of two edits. The first edit tabulates the input data in the same order as they appear in the input cards. The second edit tabulates the cross-section data at the output mesh energies, as described in Section 2.1, and arranges them in an easily readable manner.

3. THE GENERATION DATA ROUTINE PROCESSOR (GENPRO)

The cross-section data generated by GENDA may be used in various ways. However, in Monte Carlo type calculations, what has to be determined once a collision occurs, is

1. The type of event which takes place
2. The energy and direction angle of the emerging particle, if any.

The GENPRO program processes the GENDA output to tabulate probabilities peculiar to a nuclide at a prescribed energy mesh as follows.

1. It computes the probability of elastic scattering, inelastic scattering, and absorption.
2. In case of anisotropic elastic scattering, it tabulates the cosines of angles between which scattering is equi-probable.
3. In case of inelastic scattering, two possibilities exist.
 - a. If the spectrum has a continuous part, it computes energies to which the particle scatters with equal probability.
 - b. If the spectrum is representable by ν distinct levels, it tabulates the probability that the particle will scatter to the level E_ν .

It is important to note at this point that the maximum number of output energies is different for GENDA, GENPRO, and the subsequent Monte Carlo programs. Indeed, because of the need of fine tabulation of particular cross sections, GENDA

was expanded to handle 450 output energy points. On the other hand, GENPRO can only handle 401 energy points due to core storage limitations. The UNC Monte Carlo programs are further restricted to a maximum energy mesh of 81 points. Therefore, in any Monte Carlo type calculations, input to GENDA must be consistent with the above restrictions.

Also, the output energy mesh for GENDA is variable. However, if it is used in connection with GENPRO, a fixed lethargy interval must be used.

3.1 TECHNICAL DESCRIPTION

The cross-section data for each element provided by GENDA are written on a magnetic tape called the Genda Output Tape (GOT).

GENPRO uses GOT to create an Element Data Tape (EDT) which contains the following information:

1. The number of energy points, J
2. The set of final energies in increasing order E_j^G (using the given constant lethargy step).

Then, for each element,

1. The total cross section at each final energy, $\sigma_T(E_j^G)$, is transmitted to the EDT
2. The probabilities of elastic and inelastic scattering and absorption are computed.

$$P_S(E_j^G) = \frac{\sigma_S(E_j^G)}{\sigma_T(E_j^G)} \quad (21)$$

$$P_{nn'}(E_j^G) = \frac{\sigma_{nn'}(E_j^G)}{\sigma_T(E_j^G)} \quad (22)$$

$$P_A(E_j^G) = 1 - P_S(E_j^G) - P_{nn'}(E_j^G) \quad (23)$$

P_S and P_A tables are then transmitted to the EDT.

It should be noted that for neutron absorption, P_A contains both fission and capture probabilities.

3. In the event of elastic scattering, the following calculation is performed to decide whether or not the scattering is isotropic.

The angular distribution data supplied by GOT in the form of Legendre expansion coefficients f_ℓ 's is tested for each energy point. Let

$$\sigma(\omega=1) = \sum_{\ell=0}^L (2\ell + 1) f_\ell(E_j^G) \quad (24)$$

$$\sigma(\omega=-1) = \sum_{\ell=0}^L (2\ell + 1) f_\ell(E_j^G) (-1)^\ell \quad (25)$$

$$\sigma(\omega=0) = \sum_{\text{even } \ell} (2\ell + 1) f_\ell(E_j^G) P_\ell(0) \quad (26)$$

where the notation used is given in the GENDA section.

The largest and smallest of these are selected and referred to as M and m , respectively.

Then if

$$\frac{M - m}{0.5(M+m)} \leq 0.05, \quad (27)$$

the angular distribution is taken as isotropic and no further tabulated data are required. (See Section 7.)

Otherwise, the scattering is treated as anisotropic and GENPRO proceeds to compute the angles θ through which it is equally probable to scatter.

Since the differential scattering cross section is given by

$$\sigma(E_j^G, \mu) = \frac{\sigma_n(E_j^G)}{4\pi} \sum_{\ell=0}^L (2\ell + 1) f_\ell(E_j^G) P_\ell(\mu) \quad (28)$$

where $\mu = \cos \theta$ varies from -1 to +1, GENPRO computes

$$F(\mu, E_j^G) = \frac{2\pi}{\sigma_n(E_j^G)} \int_{-1}^{\mu} \sigma(E_j^G, \mu) d\mu \quad (29)$$

which gives the μ probability distribution. The integration of Eq. 28 yields

$$F(\mu, E_j^G) = \sum_{\ell=0}^L \frac{1}{2} f_\ell(E_j^G) [P_{\ell+1}(\mu) - P_{\ell-1}(\mu)] \quad (30)$$

with the convention that $P_{-1} = -1$.

$F(\mu, E_j^G)$ is computed for $-1 \leq \mu \leq +1$ in steps of 0.01. Then GENPRO locates μ_n such that

$$F(\mu_n) = \frac{n}{N} \text{ for } n = 0, 1, 2 \dots, N \quad (31)$$

N is usually 10 for the Monte Carlo programs.

For statistical considerations, it is desirable to use a new variable χ which is related to μ by

$$\mu = \cos \theta = 1 - 2\chi \quad (32)$$

where now χ varies from 0 to 1.

Hence,

$$\chi_n = \frac{1 - \mu_n}{2}, \quad n = 0, 1, 2 \dots N \quad (33)$$

is tabulated and transmitted to the EDT as Table CHI.

4. In the event of continuum inelastic scattering (which is determined by the threshold energy supplied by GOT), the probability that a neutron entering collision at energy E_j^G will emerge from an inelastic scattering collision at energy E' has been computed by GENDA and entered into GOT in the form of $g_c(E_j^G, E')$ with $E_j^G > E_{BD}$.

To obtain the energies to which it is equally probable to scatter, GENPRO calculates

$$G(E_j^G, E) = \int_0^E g_c(E_j^G, E') dE', \quad E \leq E_j^G \quad (34)$$

where the integral is evaluated by the trapezoidal rule.

Note that if one considers the spectrum of neutrons emitted by (nn') reactions, the integral (Eq. 34) is normalized to 1.

Indeed,

$$G(E_j^G, E_j^G) = 1 \quad (35)$$

However, GENDA considers the composite spectrum of neutrons emitted by (nn'; n,2n) reactions and hence, $G(E_j^G, E_j^G)$ may be different from 1

and GENPRO proceeds to compute:

$$g(E_j^G, E) = \frac{G(E_j^G, E)}{G(E_j^G, E_j^G)} \quad (36)$$

Then it locates E_n such that

$$g(E_j^G, E_n) = \frac{n}{N} \text{ for } n = 0, 1, 2 \dots, N \quad (37)$$

N is usually 10 for the Monte Carlo programs. The E_n are tabulated and transmitted to the EDT as Table ENN.

5. In the event of discrete level inelastic scattering, GOT supplies the a_ν 's. The a_ν^j 's are tabulated and transmitted to the EDT as Table PLEV (ν, j). The corresponding values of the excitation level energies are tabulated and transmitted to the EDT as Table ELEV (ν, j).

6. If both continuum and discrete level inelastic scattering occur, i.e.,

$E_{BC} < E_j^G \leq E_{BD}$, GOT supplies information on the kernels $g_C(E_j^G, E')$ and $g_D(E_j^G, E')$ and the continuum and discrete level inelastic scattering cross sections, $\sigma_{nn',c}(E_j^G)$ and $\sigma_{nn',D}(E_j^G)$.

To obtain the energies to which it is equally probable to scatter, the GENPRO program calculates the probability $G(E_j^G, E)$ that a neutron at E_j^G scatters at energy E as follows:

$$G(E_j^G, E) = \frac{\sigma_{nn',c}(E_j^G) \int_0^{E_j^G} g_C(E_j^G, E') dE' + \sigma_{nn',D}(E_j^G) \int_0^{E_j^G} g_D(E_j^G, E') dE'}{\sigma_{nn',c}(E_j^G) + \sigma_{nn',D}(E_j^G)} \quad (38)$$

where $G(E_j^G, 0) = 0$ and $G(E_j^G, E_j^G) = 1$, and the probability distribution functions g_C and g_D have been discussed in the GENDA section.

Then, GENPRO proceeds to locate the energies, E_n , to which it is equally probable to scatter as if the level spectrum was continuous only. The method used is similar to that of determining the cosines of the angles through which it is equally probable to scatter. The E_n are tabulated and transmitted to the EDT as Table ENN.

3.2 GENPRO INPUT

The input to GENPRO consists of the GENDA Output Tape (GOT) (Logical tape 9) and one card denoting the number of elements on the GOT in the format I10.

3.3 FORMAT OF THE EDT

A description of the format of the EDT follows. Since the EDT is made up of card images, the description is in terms of card images.

Item No.	No. of Entries	Card Description	Format
1	1	NENERG NENERG is the number of energies in the energy table.	I10
2	NENERG	ETABLE(1), ETABLE(2), ETABLE(3), ETABLE(4), ETABLE(5), ... ETABLE(NENERG). ETABLE is the energy mesh for all elements. ETABLE(1) is the lowest energy and ETABLE (NENERG) is the highest energy.	5E14.5
3	3	AWT, IAWT, J AWT is the floating point atomic weight. IAWT is the fixed point atomic weight. J is an end of data flag. J≠0 means this card is the last card of the EDT.	E16.8, 2I6

Item No.	No. of Entries	Card Description	Format
4	5	OF, NOW, NFI, ISI, IPIN OF≠0 means this is last card of element. NOW is the number of words in the next group of data. NFI is a file number used for identification only. ISI≠0 means the next group of data is the scatter index. IPIN≠0 means this element has no inelastic scattering.	E16.8, 4I6
5	NOW	SIGMA(1), SIGMA(2), SIGMA(3), SIGMA(4), etc. SIGMA is the microscopic total cross section. Note that NOW must equal NENERG and that OF, ISI, IPIN must all be zero.	5E14.5
6	5	Repeat item 4.	E16.8, 4I6
7	NOW	PSCAT(1), PSCAT(2), PSCAT(3), PSCAT(4), PSCAT(5), ..., PSCAT(NENERG). PSCAT is the probability of elastic scattering. PSCAT(1) corresponds to ETABLE(1) and PSCAT(NENERG) corresponds to ETABLE(NENERG).	5E14.5
8	5	Repeat item 4.	E16.8, 4I6
9	NOW	PABS(1), PABS(2), PABS(3), PABS(4), PABS(5), ..., PABS(NENERG).	5E14.5
10	5	OF, NOW, NFI, ISI, IPIN ISI must equal 1 because the next data group is the scatter index. If this element has no inelastic scattering, then IPIN must equal 1.	E16.8, 4I6
11	NENERG	IP, ID, IT, IA There are NENERG cards in this data group. Each card has the quantities IP, ID, IT, IA defined as follows: IP = 1 for inelastic discrete scattering = 2 for inelastic continuum scattering ID = the location of an ENN or PLEV table relative to the first word of the SIGMA table	4I10

Item No.	No. of Entries	Card Description	Format
11	NENERG (Cont.)	IT = 1 for isotropic scattering in center of mass = 2 for scattering in hydrogen = 3 for anisotropic scattering in center of mass = 4 isotropic scattering in the lab system ID = location of a χ Table if IT = 3.	4I10
12	5	Repeat item 4 with NOW = 11.	E16.8, 4I6
13	11	CHI(1), CHI(2), CHI(3), CHI(4), CHI(5), etc. CHI is a table of 11 entries. CHI(1) = 1.0, CHI(11) = 0. Items 12, 13 are repeated for each energy at which "IT" of item 11 is 3.	5E14.5
14	5	Repeat item 4 with NOW = 11.	E16.8, 4I6
15	11	ENN(1), ENN(2), ENN(3), ENN(4), ENN(5), etc. The ENN table is used to determine the energy after scattering for an inelastic continuum interaction. Items 14 and 15 are repeated for each energy at which "IP" of item 11 is 2. If the element has no continuum scattering items, 14 and 15 are omitted.	5E14.5
16	5	Repeat item 4 with NOW = number of excitation levels for discrete scattering.	E16.8, 4I6
17	NOW	ELEV(1), ELEV(2), ELEV(3), ELEV(4), ELEV(5), ..., ELEV(NOW). The ELEV table is a list of possible excitation levels; each entry corresponds to a probability in a PLEV table.	5E14.5
18	5	Repeat item 16.	E16.8, 4I6
19	NOW	PLEV(1), PLEV(2), PLEV(3), PLEV(4), PLEV(5), ..., PLEV(NOW). The PLEV tables are tables of probabilities of scattering from the current energy to the excitation levels. Items 18 and 19 are repeated for each energy at which inelastic discrete scattering occurs (IP=1).	5E14.5

Item No.	No. of Entries	Card Description	Format
20	5	OF, NOW, ISI, IPIN OF = 1.0. NOW, ISI, IPIN = 0. Item 20 is the last card of an element.	E16.8, 4I6
21	3	AWT, IATWT, J If there are no more elements AWT, IATWT = 0. J = 1. If there are more elements repeat from item 3.	

4. THE DATA ORGANIZATION PROGRAM (DATORG)

The GENDA and GENPRO programs are used to generate an element data tape (EDT) which contains microscopic cross sections and probability tables for all nuclides of interest. This EDT can be considered as a library tape for any subsequent Monte Carlo problems.

For a specific problem, however, the system is divided into regions which contain given nuclide compositions. Each composition may be described by a set of nuclides and their respective concentrations. When a particle enters collision at some point within a region of given composition, the Monte Carlo program has to select the nuclide in the composition with which the particle collides.

The probability that a particle with energy E will interact with nuclide k of the composition R is given by

$$P(k, R) = \frac{C_{k,R} \sigma_T(k, E)}{\mu_{T,R}(E)} \quad (39)$$

where $\mu_{T,R}(E)$ is the total macroscopic cross section of the composition, and $C_{k,R}$ is the concentration of nuclide k in region R.

$$C_{k,R} = \frac{\rho_k}{A_k} N_0 v_{k,R} \quad (40)$$

where ρ_k = density of the nuclide k

A_k = its atomic weight

$N_0 10^{24} = 0.6023 \times 10^{24}$, the Avogadro's number

$v_{k,R}$ = volume fraction of the nuclide.

4.1 TECHNICAL DESCRIPTION

The DATORG program searches and reads from the EDT all information concerning the nuclides which appear in the various core positions specified in the input. It computes the total macroscopic cross sections of each composition at each final energy, $\mu_{T,R}(E_j^G)$, using the concentration data supplied as input to the program. Finally, it stores in the COMMON portion of core all data concerning the nuclides and the composition of the problem in a prescribed order.

Hence, the role of DATORG is above all the organization of the cross section and probability data read from the EDT. In addition, it computes and stores the $\mu_{T,R}(E_j^G)$'s.

$$\mu_{T,R}(E_j^G) = \sum_{k's \text{ in } R} C_{k,R} \sigma_T(k, E_j^G) \quad (41)$$

The output energy mesh for DATORG is, of course, given by the fixed lethargy interval used to generate the EDT.

4.2 DATORG INPUT FORM

A DATORG input form is shown on the following page.

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PROJECT _____ TASK _____

ORIGINATOR _____

DATE _____

PROBLEM NO. _____

ADONIS INPUT FORM GROUP-1 DATA

Type Problem:

- Gamma
 Neutron

DATORG

TITLE CARD

TITLE - ALPHABETICS AND NUMERICS ACCEPTABLE

Deck I.D. No.*

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80

X.S.DAT.1.01

PROBLEM IDENTIFICATION CARD (TO BE FILLED OUT ONCE ONLY)

Deck I.D. No.*

Problem number	Upper energy of cross-section data, ev	Lower energy of cross-section data, ev
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
E +	E +	E +

X.S.DAT.1.02

REPEAT FOLLOWING FOR EACH COMPOSITION

COMPOSITION I.D. CARD

Deck I.D. No.*

Composition number (> 100)	No. of elements (≤ 5)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
E -	E -

X.S.DAT.1.03

ELEMENT CARDS

Deck I.D. No.*

Atomic weight integral point only	Concentration = $\frac{\rho N_A}{A}$ x volume fraction $\times 10^4$
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
E -	E -
E -	E -
E -	E -
E -	E -
E -	E -
E -	E -
E -	E -

X.S.DAT.1.1

X.S.DAT.1.1

X.S.DAT.1.1

X.S.DAT.1.1

X.S.DAT.1.1

X.S.DAT.1.1

X.S.DAT.1.1

*Every card is to be numbered sequentially.

4.3 DESCRIPTION OF THE OUTPUT DATA

The data stored by DATORG contains the following items in their order of listing.

Symbol	No. of Locations	Definition
Counters		
NORG	1	Counter denoting number of words in the array XSECT.
NELEM	1	Counter denoting number of distinct nuclides (≤ 33).
NR	1	Counter denoting number of compositions (≤ 20).
NENERG	1	Counter denoting number of energies (≤ 100).
JK	1	Counter denoting the sum of all nuclides in every composition.
Tables		
NEL	NR	Number of nuclides for each composition (≤ 5 for any composition).
NEVAT	NELEM	Integral value of atomic weight of each nuclide desired. Elements arranged in the order read from EDT (i.e., if oxygen = 16.0, hydrogen = 1.0, Fe = 55.85 are desired and they appear on the EDT as 16, 55.85, 1.0, then NEL(1) = 16, NEL(2) = 55, NEL(3) = 1. Furthermore, oxygen will be referred to as element 1; Fe, as element 2, etc.).
EVAT	NELEM	Corresponding to each element in NEVAT the actual atomic weight is entered in EVAT.
IATWT	$\sum_{i=1}^{NR} NEL_i$	IATWT contains for each composition in the order of composition number the element number (see NEVAT) of each element of the composition in the order specified by the input.
CONCT	$\sum_{i=1}^{NR} NEL_i$	Corresponding to each entry in IATWT the concentration of the element is placed in CONCT.
KPHYS	NR	There is one entry for each composition and each entry contains the N_i where $N_i = N_{i-1} + NEL_{i-1} + 1$, $NEL_0 = N_0 = 0$.

Symbol	No. of Locations	Definition
XSECT	(Variable dimension)	Contains the cross section and the probabilities for each prescribed element. They are given in the order in which they are obtained in GENPRO (and appear in the EDT). Also contains macroscopic cross sections for each composition in the order of composition number.
NSECT	NELEM	Contains the origin relative to start of XSECT for each element (in the order specified by NEVAT).
MUTORG	NR	Contains origin of location of the tables of total cross sections, μ_T , in XSECT which are written in the order of composition number.

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5. THE GENERATION OF SOURCE PARTICLES FOR MONTE CARLO PROBLEMS

The Monte Carlo Game played in the solution of the neutron and gamma transport calculations is one in which a simulated particle is followed through all the processes with associated probability that a real particle would follow. Many such particles are tracked, and score their contribution to any physical or mathematical quantity that is desired. The tracking of a primary particle from its birth through its descendants to their disappearance from the given system (by absorption, degradation, or leakage) is defined as a history.

A particle is characterized at any instant by its space position \underline{P} , its direction $\underline{\Omega}$, and its energy E (neglecting effects like spin and interference phenomena).

The first step is to determine by sampling \underline{P} , $\underline{\Omega}$, and E of the virgin particle from a normalized source distribution $S(\underline{P}, E, \underline{\Omega})$.

The volume anisotropic source generator (VANGEN) is used to select from a combination of several types of spatial, angular, and energy distributions of the primary particles.

Now, if either inelastic scatterings or absorption occur in the course of tracking neutrons, the primary Monte Carlo program (ADONIS) will record on an interaction tape the identity of the source particle which is being tracked, the location and the incident energy of the neutron at the interaction, the type of interaction,

and the element with which the neutron collided. This is done for possible secondary source generation.

The secondary gamma source particle generator (GASP) uses the interaction tape along with input data which characterize the number and energies of gammas born following an inelastic scattering or an absorption for each element to create a secondary source tape which can be used for subsequent Monte Carlo programs.

It should be noted that GASP can be used to generate other types of secondary source particles (α , β , fission products, ...) by judicious choice of input data. In particular, GASP has been used to create a source for neutrons produced by fission.

An important feature in the UNC Monte Carlo programs is that the generation of source particles has been arranged in such a manner that anyone with a fundamental knowledge of FORTRAN programming may create a source particle generator complying with his own needs.

5.1 VANGEN

VANGEN selects from a given combination of spatial, angular, and energy distributions a specified number of primary neutron or gamma source particles and records on a source tape a number which identifies the particle, its position in Cartesian coordinates, the three direction cosines of its initial direction, its energy, and the region number in which the particle was born.

There are numerous types of distributions that can be thought of, and if the need arises, a technique can be devised to select from any of them.

In the present programs, we have restricted ourselves to the more commonly used distributions.

5.1.1 Spatial Distributions

Volume Source

It is assumed that the particles are uniformly distributed in a given parallelepiped that must be fully contained in one region of the specified geometrical system. As in EZGEOM (see Section 6), the "ordinary rectangular parallelepiped" must be described by its six bounding planes: $x_\alpha, x_\beta, y_\alpha, y_\beta, z_\alpha, z_\beta$.

If ξ_1, ξ_2, ξ_3 , are three random numbers between 0 and 1, the position of the source particle is given by:

$$\begin{aligned} x &= x_\alpha + \xi_1 (x_\beta - x_\alpha) \\ y &= y_\alpha + \xi_2 (y_\beta - y_\alpha) \\ z &= z_\alpha + \xi_3 (z_\beta - z_\alpha) \end{aligned} \quad (42)$$

Plane Source

If, in the volume source description, we make $x_\alpha = x_\beta$ (or $y_\alpha = y_\beta$, or $z_\alpha = z_\beta$), one obtains the uniform distribution in a plane perpendicular to one of the coordinate axes. Note that if a plane source is used, it must be inside the given source region and cannot be coincident with one of the six bounding planes of this region.

Point Source

If we now make $x_\alpha = x_\beta, y_\alpha = y_\beta, z_\alpha = z_\beta$ in the volume source description and if $x_\alpha, y_\alpha, z_\alpha$ are the coordinates of the point source, then one gets the desired distribution.

5.1.2 Energy Distribution

Method by Equal Probability Steps

If the number of source particles in energy range ($E, E + dE$) is given by the function $N(E)dE$, the input to VANGEN must be prepared as follows.

Compute the probability $f(E)$ by any available method of integration:

$$f(E) = \frac{\int_{E_0}^E N(E)dE}{\int_{E_0}^{E_{\max}} N(E)dE} \quad (43)$$

where E_0 and E_{\max} are the lower and upper energies of the distribution respectively.

Hence, $f(E_0) = 0$, $f(E_{\max}) = 1$.

Determine the E_η 's such that

$$(E_\eta) = \frac{\eta}{M} \text{ for } \eta = 0, 1, \dots, M \quad (44)$$

where M is the number of equal probability steps that is selected ($M < 100$).

The input will consist of the number of equal probability steps plus 1 ($M+1$), the width of the probability interval ($1/M$) and the upper and lower energy limits of each step (i.e., for step η , $E_{\eta-1}$ and E_η).

The program will select a random number, ξ , between 0 and 1 and take the integral portion of $1 + [\xi/(1/M)] = 1 + M\xi$. This will determine the energy bin in which the energy of the source neutron must be selected. For example, if the integral portion of $1 + M\xi$ is equal to η , the $E_{\eta-1} \leq E \leq E_\eta$. In the energy bin itself, the energy E is selected assuming a uniform distribution.

$$E = E_{\eta-1} + \alpha(E_\eta - E_{\eta-1}) \quad (45)$$

where

$$\alpha = \frac{\xi - [M\xi]}{\frac{1}{M}} \frac{1}{M}$$

with $[M\xi]$ = integral portion of $M\xi$.

Fission Spectrum

The number of neutrons in the energy range $(E, E + dE)$ is given by

$$N(E)dE = A e^{-\alpha_1 E} \sinh \sqrt{\alpha_2 E} dE \quad (46)$$

where α_1 , α_2 , and A are constants and $E_L < E < E_U \geq 0$ and $E_U \leq \infty$ are the lower and the upper limits of the fission spectrum respectively.

The method described in the foregoing section may be applied. However, the program uses an elegant rejection technique invented by M.H. Kalos⁶ in order to pick E from the probability distribution given by Eq. 46.

Briefly, an energy E is chosen as follows.

Suppose

$$p_1(x)dx = \frac{e^{-x}dx}{e^{-x_1} - e^{-x_2}} \quad x_1 \leq x \leq x_2 \quad (47)$$

$$p_2(y)dy = e^{-y} dy \quad 0 \leq y < \infty \quad (48)$$

If

$$-ax + (y - bx - c)^2 \leq 0, \quad (49)$$

choose

$$E = \gamma x \quad (50)$$

Otherwise, reject and repeat from Eq. 47.

To obtain the right fission distribution and insure a maximum efficiency for the rejection technique, the parameters a , b , c , γ have been evaluated using the latest experimental fit for the fission spectrum of prompt neutrons.

$$a = 4.572573$$

$$b = 1.069179$$

$$c = 1.069179$$

$$\gamma = 1.99675$$

and in Eq. 46,

$$x_1 = \frac{E_L}{\gamma} \quad x_2 = \frac{E_U}{\gamma}.$$

Monoenergetic Source

If the upper and lower limits of the fission spectrum are made equal to the desired energy, one obtains the monoenergetic distribution.

5.1.3 Angular Distribution

Anisotropic Angular Distribution

If the angular distribution of the source particles is symmetric about an axis, $\underline{\Omega}_0$, one can divide the total solid angle into M intervals, each interval being defined by the scalar product of the angle of the cones with $\underline{\Omega}_0$, i.e., interval i is defined by W_{i-1} and W_i such that

$$W_{i-1} = \underline{\Omega}_{i-1} \cdot \underline{\Omega}_0 \quad (51)$$
$$W_i = \underline{\Omega}_i \cdot \underline{\Omega}_0$$

In each of these intervals, the number of source particles is given with probability p_i ; such that

$$\sum_{i=1}^M p_i = 1.$$

The program will select a random number ξ between 0 and 1, and compare it to

$$\sum_{i=1}^j p_i,$$

where $j \leq M$.

If

$$\sum_{i=1}^{j-1} p_i \leq \xi \leq \sum_{i=1}^j p_i, \quad (52)$$

then the direction of the source particle is selected from the j^{th} interval.

The direction cosine in the j^{th} interval is then chosen with equal probability. Thus

$$W = W_{i-1} + \xi' (W_i - W_{i-1}). \quad (53)$$

where ξ' is another random number.

The azimuthal angle is also chosen at random between 0 and 2π .

Isotropic Angular Distribution

The isotropic case is obtained by making $M = 1$, $W_0 = -1$, $W_1 = +1$, and $p_1 = 1$ in the anisotropic distribution.

Monodirectional Distribution

In this case, it is sufficient to take $M = 1$, $W_0 = W_1 = \pm 1$ and $p_1 = 1$ in the anisotropic distribution. Of course, directions parallel to each coordinate axis in both positive and negative directions can be obtained by choosing the axis direction, Ω_0 .

The numbers 1, 2, or 3 submitted as input indicate that the source will be generated about the x, y, or z axis respectively.

5.2 GASP

GASP selects the energy of secondary gammas produced by neutron inelastic scattering and absorption which includes capture, fission, and production following a charged particle reaction. The position of these secondary source gammas is read from the interaction tape and their direction can be selected as in VANGEN. The output is written on the source tape.

For each element of interest (specified by the integral part of its mass number) for both absorption and inelastic scattering and for a given number of energy intervals for the incident neutrons, the GASP data input consists of

1. A table which contains the gamma energies in increasing order,
 $E_{\gamma\ell} \quad \ell = 1, 2, \dots, L \leq 10.$
2. A table which lists the lower and upper energies of the neutron bin intervals, E_k , $k = 0, 1, \dots, K \leq 30$, such that the k^{th} energy bin is given by the interval (E_{k-1}, E_k) .
3. A list of the expected number of gammas of energy $E_{\gamma\ell}$ born in an interaction with a neutron whose initial energy lies in the interval (E_{k-1}, E_k) ,
 $N_{\gamma\ell,k}$

The GASP program proceeds to select L random numbers, $\xi_1, \xi_2, \dots, \xi_\ell, \dots, \xi_L$. The integral part of $N_{\gamma\ell,k}$ plus a Russian roulette method for the fractional portion is used to determine the number of source gammas at energy $E_{\gamma\ell}$. For in-

stance, if $N_{\gamma\ell,k} = 3.5$ and ξ_ℓ is the corresponding random number, ξ_ℓ is compared to 0.5. If $\xi_\ell > 0.5$, then four gammas are taken with energy $E_{\gamma\ell}$. If $\xi_\ell < 0.5$, three gammas are taken with energy $E_{\gamma\ell}$.

Further, if, in the ADONIS problem, weights W_n and W_γ are attached to the region in which the interaction takes place, the number of gammas obtained is multiplied by the ratio W_n/W_γ , and the number of source gammas is obtained again by taking the integral fraction of the product plus the result of the Russian roulette played with the fractional portion of the product.

Gamma production by radiative neutron capture, fission, and charged particle reaction, i.e., (N,P), must be included in the input for the gamma production by absorption.

Thus, the input must be the expected number of gammas born by neutron absorption given by

$$N_{\gamma\ell}^A = \frac{\sigma_c^C N_{\gamma\ell}^C + \sigma_f^F N_{\gamma\ell}^F + \sigma_p^P N_{\gamma\ell}^P}{\sigma_c^C + \sigma_f^F + \sigma_p^P} \quad (54)$$

where σ denotes a cross section and the superscripts c, F, A, and P denote capture, fission, absorption, and charged particle reaction, respectively.

5.3 VANGEN INPUT DESCRIPTION

The VANGEN input is described as follows (columns 73 to 80 are for identification):

5.3.1 Card 1 (contains parameter input for VANGEN)

Column	Item	Format
1-10	The number of source particles to be generated.	I
15	The normal direction of the source: 1 = x-direction, 2 = y-direction, 3 = z-direction	

Column	Item	Format
18-20	The number of the region where the source particle will be born.	I
23-25	If the energy distribution is chosen at equal probability intervals, this entry contains the number of energy intervals + 1. If the fission spectrum option or monoenergetic option is desired, the entry is 0.	I
26-37	The entry for the upper energy limit of the fission spectrum desired, E_U (0 if this option is not desired).	E
38-49	The entry for the lower energy limit of the fission spectrum desired, E_L (0 if this option is not desired).	E

Note:

For monoenergetic problems, $E_U = E_L$ and entries in the columns 23 through 25 should be 0.

5.3.2 Card 2 (contains the desired spatial distribution)

Column	Item	Format
1-12	The x_α bounding plane of the source volume.	6E12
12-24	The x_β bounding plane of the source volume.	
25-36	The y_α bounding plane of the source volume.	
37-48	The y_β bounding plane of the source volume.	
49-60	The z_α bounding plane of the source volume.	
61-72	The z_β bounding plane of the source volume.	

Notes:

1. If $x_\alpha = x_\beta$, or $y_\alpha = y_\beta$, or $z_\alpha = z_\beta$, plane source distribution is obtained.
2. If $x_\alpha = x_\beta$, $y_\alpha = y_\beta$ and $z_\alpha = z_\beta$, point source distribution is obtained.

At the present time, the spatial distribution must be contained in one and only one region.

The next set of cards contains information on the energy distribution in equal probability steps if desired. (Use only if columns 23 to 25 on card 1 are nonzero.)

The first entry is the probability step. It is then followed by the energies (in ev) in increasing order. (These energies are the limits of energy bins.) The number of energies is one more than the number of bins. There are six entries per card. The format is 6E12.5.

Three types of cards describe the angular distribution:

1. The Bin Information Card

Contains the number of angular bins + 1 in columns 3-4.

2. The Angular Bin Card

These cards contain the cosine limits of each angular bin. There are seven entries per card and the format is 7E10.4. [The lower limit of the $(i+1)^{\text{th}}$ bin is the upper limit of i^{th} bin.]

3. The Probability Card

The first entry is 0 and each entry contains the corresponding probability for each angular bin starting with the first angular bin. There are seven entries per card and the format is 7E10.4.

Note:

If an isotropic source in the forward half plane is desired, only one angular bin is necessary. The input then is:

Card type 1	2	Two cosines define bin 1
Card type 2	0.0 1.0	The lower and upper limits of the bin
Card type 3	0 1.0	The probability that a particle will be born in bin 1 is 1.

5.4 GASP INPUT DESCRIPTION

The GASP input is described as follows:

5.4.1 Element Parameter Card

This card contains the number of elements used in the associated ADONIS problem. The format is I5.

5.4.2 Element Input Data (for each element)

1. Element Parameter Card

Column	Item	Format
1-5	Integral part of the atomic mass (identification of element same as that specified in DATORG input)	
6-10	L_A = number of absorption gamma output energies (≤ 10) (0 if no capture γ produced)	I
11-15	K_A = number of corresponding incident neutron energies (≤ 30). This equals the number of neutron energy bins + 1 (0 for no γ capture).	I
16-20	L_I = number of inelastic γ out energies (≤ 10)	I
21-25	K_I = number of corresponding incident neutron energies (≤ 30). This equals the number of neutron energy bins + 1.	I

2. Capture γ Energy Cards (as many as necessary)

The energies are given in ascending order in ev. The number of entries per card is six and the format is 6E12.6. The total number of entries is equal to L_A .

3. Capture Neutron Energy Cards (as many as necessary)

Every two entries represent a neutron energy bin. The entries are in ascending order and in ev. There are six entries per card and the format is 6E12.6.

4. Capture Number Cards

Each entry represents the number of gammas produced at each of the specified γ energies. These numbers are entered for each neutron energy bin. The first L_A entries are 0 representing the 0th bin.

Start a new card for each neutron bin. There are six entries per card and the format is 6E12.6.

Repeat items 2, 3, and 4 for inelastic scattering input, if any.

5.4.3 Weights for Neutron and Gamma Problem Input (See Section 7.3.1)

1. Number of Regions Card

Enter the number of regions used in the associated neutron and gamma problems (I5 format).

2. Enter the weight for each region used in the neutron problem (format 5E14.8). (Note: there is only one entry per region. At the present time one cannot use energy importance in the neutron problem and run the secondary γ -ADONIS. It is anticipated that this restriction will be removed in the near future.)
3. Enter the weight for each region to be used in the secondary gamma problem (format 5E14.8).

5.4.4 Angular Distribution

The angular distribution input is the same as for VANGEN.

5.5 DESCRIPTION OF THE SOURCE TAPE

The source tape which is generated by both VANGEN and GASP must conform to the specifications required by the ADONIS program. Particles must be generated in groups of 100. Each particle is described by nine numbers:

- 1 the particle number
- 2-4 the location of the particle in 3-space (its x-y-z coordinates)
- 5-7 the three direction cosines the particle assumes initially
- 8 the initial energy of the particle
- 9 the region number in which the particle is born.

With the exception of the particle number and the region number, the entries are in floating point notation, and are generated by a FORTRAN routine using the "WRITE TAPE" statement for 100 particles, with nine entries for one particle preceding the nine entries for the next. Finally, to signal the end of the source particles that one wants to generate, one additional particle whose particle number is -1 is necessary.

5.6 SOURCE INPUT

The source input consists of either VANGEN or GASP input forms. See following pages.

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ADONIS SOURCE GENERATOR
VANGEN

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PROBLEM INFORMATION CARD (ONCE ONLY)

No. of source particles to be generated (~ 250,000)	Normal direction of source	Region no. of points (~ 80)	No. of energies to be specified (~ 100)	E upper of fission spectrum, ev	E lower of fission spectrum, ev (see note)	Card I.D. No.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	V A N G E N

COORDINATE OF SOURCE CARD (ONCE ONLY)	
X _β coordinate	X _β coordinate

X _α coordinate	Y _α coordinate	Y _β coordinate	Z _α coordinate	Z _β coordinate	Card I.D. No.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	V A N G E N

ENERGY CARD (AS MANY CARDS AS NEEDED)	
First card: probability step of energy distribution. All other cards: continuation of energy values.	Energy, ev Lowest value first

*No. sequentially

Note: Fill in only if Ngc of energies to be specified is = 0.

BIN INFORMATION CARD (ONCE ONLY)

NOTE: Two consecutive entries correspond to an angular probability bin (i.e., 24 bins 25 entries)

No. sequentially

GAMMA SOURCE PRODUCTION (GASP)
Page 1 of 8

Page 1 of 8

ADONIS SOURCE GENERATOR

CONTINUATION OF GASP
Page 2 of 8

ADONIS SOURCE GENERATOR (CONTINUED)

ELEMENT PARAMETER CARD (ONCE ONLY)

No. of elements (15)	Card I.D. No.														
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

UNTIL NOTED OTHERWISE, REPEAT ALL OF THE FOLLOWING CARDS FOR EACH ELEMENT

ELEMENT CARDS (ONE PER ELEMENT)

Integral part of mass No.	No. of capture energies (· 10)	No. of capture neutron energies (30)	No. of inelast. neutron energies (10)	No. of inelast. neutron energies (30)	Card I.D. No. •														
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15	1	2	3	4	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

*No. sequentially

CAPTURE SAIMA ENERGY CARDS (AS MANY AS NECESSARY)

CAPTURE NEUTRON ENERGY CARDS (AS MANY AS NECESSARY)

No. sequentially

CAPTURE NUMBER CARDS

For all gamma energies at each neutron energy.
Start a new card for each neutron energy.

* No. sequentially

CONTINUATION OF GASP
Page 5 of 8

ADONIS SOURCE GENERATOR (CONTINUED)

CONTINUATION OF GASP
Page 5 of 8

No. sequentially

DISCONTINUE REPEAT FOR EACH ELEMENT INSTRUCTION

No sequentially

BIN INFORMATION CARD (ONCE ONLY)

No. of angles (≤ 25)	Card I.D. No.
1	G_A_S_P_1_1_1

ANGULAR BIN CARD (AS MANY AS NECESSARY)

| $\cos \phi = \omega$
(see note) | $\cos \phi = \omega$ |
|--|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 | E_1_1_1 |
| • 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 | E_1_1_1 |
| • 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 | E_1_1_1 |
| • 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 | E_1_1_1 |
| • 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 | E_1_1_1 |

NOTE: Two consecutive entries correspond to an angular probability bin
(i.e., 24 bins = 25 entries)

PROBABILITY PER BIN CARD 'SAME NUMBER AS ABOVE'

| Card I.D. No.* | Card I.D. No. |
|--|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 | E_1_1_1 |
| • 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 | E_1_1_1 |
| • 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 | E_1_1_1 |
| • 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 | E_1_1_1 |
| • 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 | E_1_1_1 |

*No. sequentially

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6. THE ORGANIZATION OF THE GEOMETRY DATA (EZGEOM)

Monte Carlo programs track simulated particles through a specified geometrical configuration, undergoing all the interactions that an actual particle is expected to undergo. The particle flight may pass through media having different properties. Therefore, it is of primary importance to know at all times in which medium the particle is, when the particle leaves the medium, and which medium it will be entering. Different media may be described as containing given material compositions in three-dimensional geometrical figures.

However, it is necessary to decompose these figures into particular geometrical forms which can be handled by the ADONIS program, i.e., nonintersecting rectangular parallelepipeds, right cylinders, spheres, and right wedges.

The EZGEOM program processes the input which consists of the description of the desired configuration by means of these elementary geometrical forms and stores the information into tables for rapid data access in subsequent Monte Carlo programs.

6.1 DEFINITIONS AND NOTATION

The three-space coordinate system used in describing the geometry is a Cartesian right-handed coordinate system. The x, y, z directions will be described as x_1 , x_2 , x_3 .

The entire three-dimensional space is initially decomposed into a set of rectangular parallelepipeds whose bounding planes are parallel to the coordinate axes. These parallelepipeds are called ordinary regions and are described by the coordinates of their six bounding planes: x_i^α , x_i^β with $i = 1, 2, 3$ and $x_i^\alpha \leq x_i^\beta$.

Any elementary geometrical form which is completely described in the input by a vertex V (x_1, x_2, x_3) and a set of vectors and scalars is called a nonordinary region. Nonordinary regions presently handled by EZGEOM and geometry tracking routines are spheres, right cylinders, rectangular parallelepipeds, and right wedges. In the near future, right frusta of cones will be handled by these routines.

Due to storage restrictions and word length requirements, the following rules must be observed when preparing EZGEOM input.

1. Nonordinary regions must be wholly contained in either an ordinary or a nonordinary region. Due to possible round-off errors, it is suggested that no surface of a contained region be closer to any surface of the containing region than 10^{-6} times the maximum coordinate found on the surface of the containing region. Note that the geometry is first decomposed into ordinary regions. Hence, a nonordinary region may contain a set of nonordinary regions, but must eventually be itself part of a set of regions which are wholly contained in an ordinary region.
2. The total number of ordinary and nonordinary regions must be less than or equal to 200.
3. At most, 127 nonordinary regions may be used.
4. A nonordinary region I must be wholly contained in another region E. Let region E be defined as the region external to I. At the most, seven such regions may have E as an external region. We will say that any region

may see only seven regions. In turn, each of these regions may see, at most, seven regions.

5. The geometry input must be submitted as follows:

First, define the ordinary regions and number them from 1 to M, M being the number of ordinary regions.

Then, define the nonordinary regions (by geometrical category and coordinate data) and number them starting from M + 1.

6. The data required to describe the nonordinary regions for the input are:

a. Spheres

Specify the vertex V at the center and the scalar R denoting the radius.

b. Right Cylinders

Specify the vertex V at the center of one base, a height vector, H, expressed in terms of its components, and a scalar R denoting the base radius.

c. Rectangular Parallelepipeds

Specify the vertex V at one of the corners and a set of three mutually perpendicular vectors, α_i , representing the height, width, and length of the parallelepiped respectively. Note that the bounding planes need not be parallel to the coordinate axes.

d. Right Wedges

The input is the same as for the nonordinary rectangular parallelepipeds. However, the first two vectors describe the two legs of the right triangle of the wedge.

e. Right Frusta of Cones

Specify a vertex V at the center of the lower base, the height vector, H , expressed in terms of its components, and two scalars, R_1 and R_2 , denoting the radii of the lower and upper bases respectively. (The frusta of cones is expected to be included in the geometry description in the near future.)

6.2 TECHNICAL DESCRIPTION

The EZGEOM routine considers first the ordinary regions and proceeds to find the regions adjacent to each side of the ordinary parallelepipeds, starting with region number 1.

Let $x_{i,m}^\alpha$, $x_{i,m}^\beta$ be the coordinates of the six bounding planes of the ordinary region, m ($1 \leq m \leq M$, M being the total number of ordinary regions). The routine starts with $x_{1,1}^\alpha$ and compares it to $x_{1,m}^\beta$ for $m = 2, 3, \dots, M$.

Suppose that $x_{1,1}^\alpha = x_{1,m}^\beta$, then the x_1^α face of region 1 and the x_1^β face of region m are on the same plane. This case is illustrated by Fig. 4.

It is necessary to determine whether or not the two faces have an area in common. Hence, the program proceeds to test:

1. $x_{2,1}^\alpha : x_{2,m}^\beta$. If greater than or equal, there is no overlap and the routine considers the next region (Fig. 4 and case a of Fig. 5). If less than, then the second test is tried.
2. $x_{2,1}^\beta : x_{2,m}^\alpha$. If less than or equal, there is no overlap and the routine considers the next region (case a, Fig. 5). If greater than, then the third test is tried.

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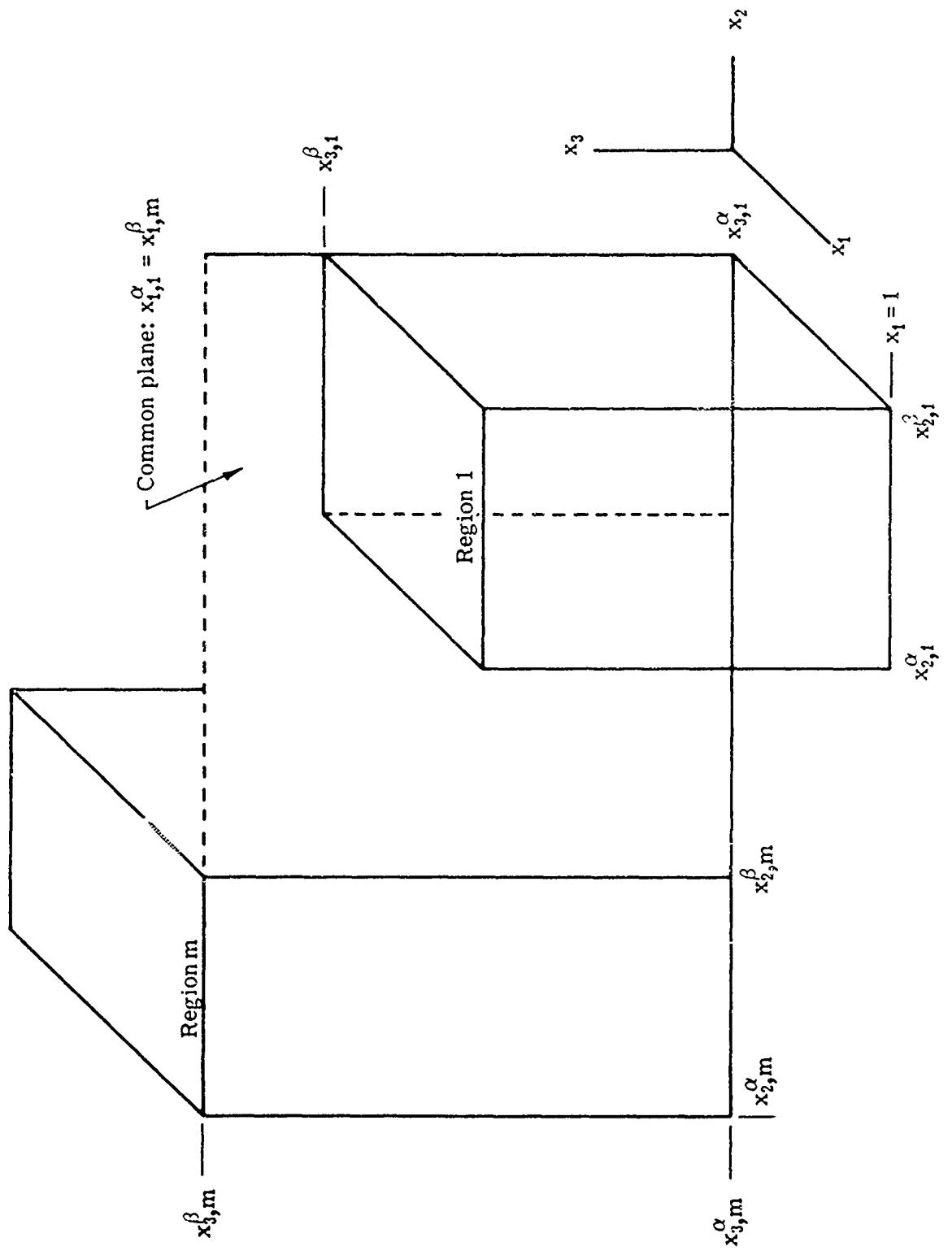


Fig. 4 — Case where regions 1 and m have a face lying in a common plane ($x_{1,1}^\alpha = x_{1,m}^\beta$) with no overlapping

8

Case a
(No overlapping in the x_2 direction
 $(x_{2,1}^{\alpha} \geq x_{2,m}^{\beta})$)

Case b

(Overlapping in the x_2 direction
but no overlapping in the x_3
direction)
 $x_{2,1}^{\alpha} < x_{2,m}^{\beta}$
 $x_{2,1}^{\beta} > x_{2,m}^{\alpha}$
 $x_{3,1}^{\alpha} > x_{3,m}^{\beta}$

Case c

(Overlapping in both the x_2 and x_3
directions)
 $x_{2,1}^{\alpha} < x_{2,m}^{\beta}$
 $x_{2,1}^{\beta} > x_{2,m}^{\alpha}$
 $x_{3,1}^{\alpha} < x_{3,m}^{\beta}$
 $x_{3,1}^{\beta} > x_{3,m}^{\alpha}$

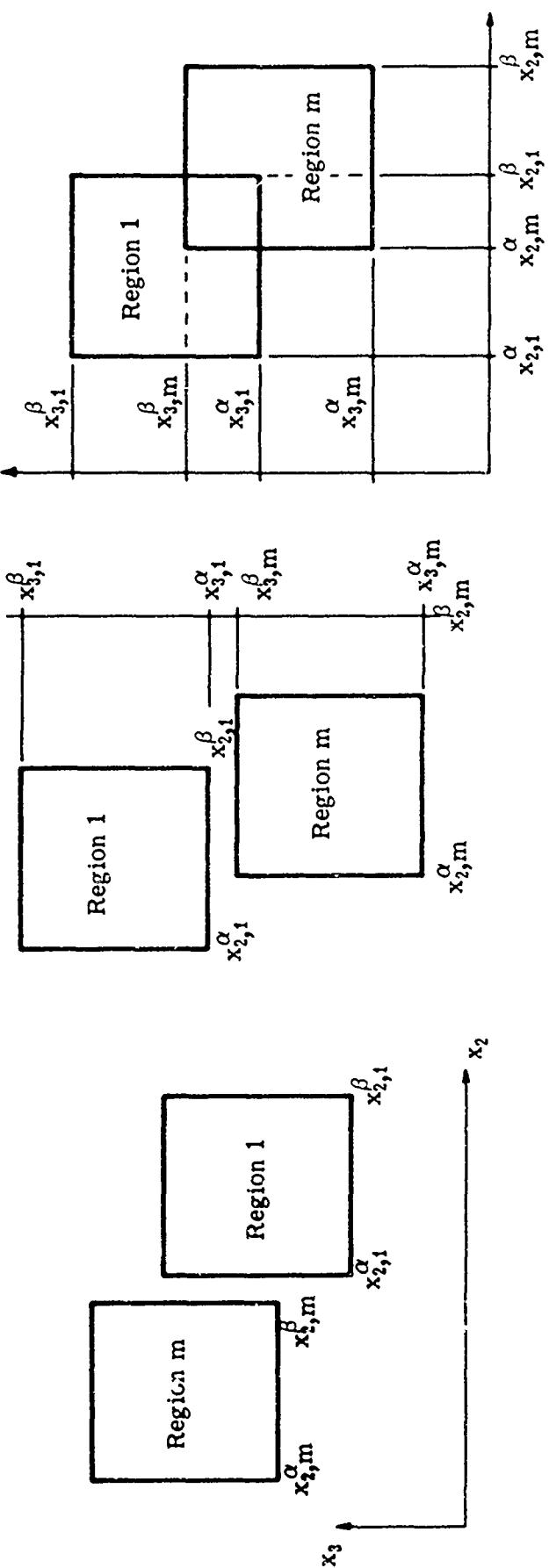


Fig. 5 — Case where regions 1 and m have a face lying in a common plane ($x_{1,1}^{\alpha} = x_{1,m}^{\beta}$)

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3. $x_{3,1}^\alpha \leq x_{3,m}^\beta$. If greater than or equal, there is no overlap (case b, Fig. 5) and the comparison to the $m + 1$ region is considered. If less than, then the fourth and last test is tried.
4. $x_{3,1}^\beta \leq x_{3,m}^\alpha$. If less than or equal, there is no overlap (case b, Fig. 5) and the comparison to the $m + 1$ region is considered. If greater than, then there is an area in common (case c, Fig. 5). In this case, the region m is stored in a table in which all regions adjacent to region 1 are recorded.

Once the comparison of $x_{1,1}^\alpha$ to $x_{1,m}^\beta$ for all m is completed, the number of regions contained in the table is tested.

1. If there is no adjacent region, the coordinate $x_{1,1}^\alpha$ is an extremity for the geometry and the region adjacent to region 1 on the x_1^α face is itself. This coordinate is saved. Then, if in the course of the investigation of the x_1^α coordinate of other regions another extremity is found which is not equal to $x_{1,1}^\alpha$, it means that the geometry has not been properly defined. This diagnostic is printed, and the program is stopped.
2. If there is only one region, the region number is placed in the proper table as the region adjacent to region 1 on the x_1^α face. Further, a flag is set to denote that region 1 is adjacent to that region, say region m . Thus, when the x_1^β face of region m will be investigated, there is no need to search for regions in contact with it if their region number is less than m . The procedure is followed for regions whose number is greater than m only.
3. If there is more than one region in contact with the $x_{1,m}^\alpha$ face of a given region, the $x_{1,m}^\alpha$ face is defined as a complex surface. The EZGEOM program proceeds to decompose the complex surface into a grid of elementary rectangles and assign to each of them the corresponding region number.

Let us consider the complex surface oriented such that the normal to that plane is in the positive direction. The horizontal and the vertical directions are determined, using the right-handed method, i.e., if the x_2 -axis is normal to the complex surface as in the case shown in Fig. 6, then the x_1 and x_3 axes are the horizontal and vertical directions respectively.

The first step performed by the routine is to extract the β coordinates in the horizontal direction of all adjacent regions and place them in increasing order removing duplicated coordinates, say $H_1, H_2, \dots, H_{\max}$.

The second step is to test if H_{\max} is greater than or equal to x_2^β of the region investigated. If it is, x_2^β replaces H_{\max} in the table. If it is less, this means that there is an area on the right side of the face which has not been accounted for. A diagnostic is printed pointing out that a hole exists and the program is stopped.

The same sequence of operations is performed for the β coordinates in the vertical direction, say $V_1, V_2, \dots, V_{\max}$.

These horizontal and vertical sequences determine a two-dimensional matrix. The complex surface is thus decomposed in a grid of rectangles. The EZGEOM program proceeds to place in each of these rectangles the corresponding region number. It must be noted that several rectangles may belong to a given region. This is done as follows: let $x_{2,m}^\alpha, x_{2,m}^\beta$ be the coordinates in the horizontal direction of the adjacent region m . The program determines the number of intervals H_i contained in $[x_2^\alpha, x_2^\beta]$. Clearly, there must be horizontal coordinates in the horizontal sequence which equal to x_2^α and x_2^β . If not, either a hole or an overlap exists and a diagnostic is printed giving the region number under consideration, the plane being searched, the table of adjacent regions found, and the horizontal and vertical tables. From this information, it is possible to construct the complex surface and find the error.

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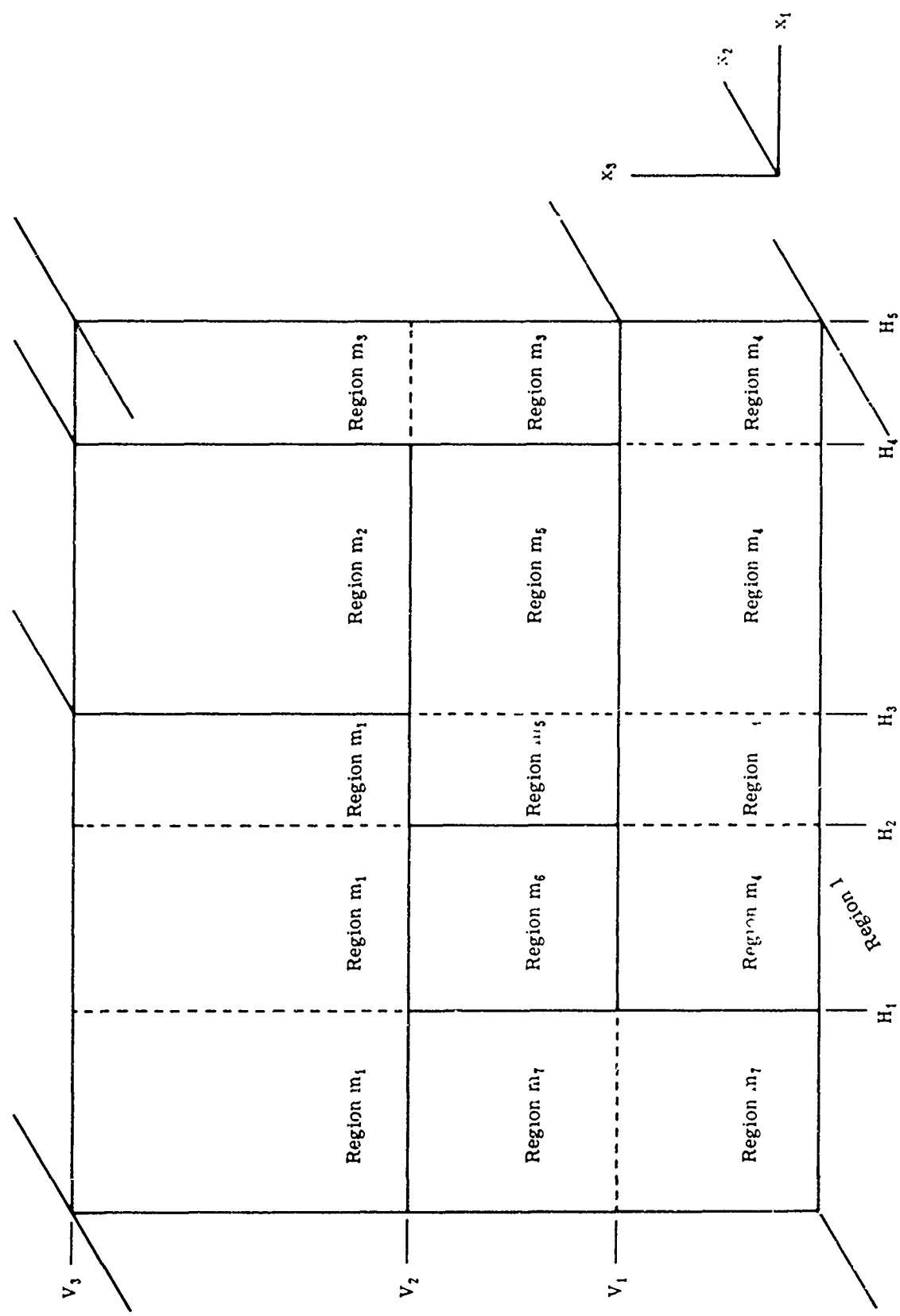


Fig. 6.—Illustration of the EZGEOM decomposition of a complex surface

If no error has occurred, the data gathered for the complex surface are placed in Table 3 which is described in Section 6.3.

The same procedure is repeated for each face of each region.

When all ordinary regions have been processed, the input cards for the nonordinary regions are read and stored according to the format described in Section 6.3.

At the present time, there is no routine built into EZGEOM which verifies that the submitted input for the nonordinary region is properly defined. Consequently, extreme care should be taken in preparing input data for nonordinary regions.

In conclusion, it is believed that EZGEOM will find most, if not all, errors made in the input data for ordinary geometry. It is possible for EZGEOM to fail to give a diagnostic when the programmed dimensions of a table for complex surfaces are exceeded. This may occur when a complex surface is defined by a grid of more than 20×20 rectangles and the investigated region is located near the end of the ordinary region listing. This is an instance when an incorrect edit can be obtained. In this case, all the regions adjacent to region 1 will be called region 1, showing that the geometry was handled incorrectly. In general, the situation is improved by assigning a very low region number to that region.

6.3 DESCRIPTION OF THE INPUT-OUTPUT

6.3.1 Input

1. The first card contains the number of ordinary regions, M , and the number of nonordinary regions, N ($N \leq 127$). Note that $M + N \leq 200$.
2. The next M cards contain the coordinates of the six bounding planes of each region: $x_i^\alpha, x_i^\beta; i = 1, 2, 3; x_i^\alpha < x_i^\beta$. Note that the cards are placed in the same order as the region numbers.

3. The input for each of the N nonordinary regions has been described in the definitions (Section 6.1). The order in which the cards are placed is also according to the region numbers ($M + 1$ to $N + M$).

6.3.2 Output

The output edit gives a complete description of each region and is self-explanatory.

EZGEOM generates three tables which completely describe the geometry specifications for the problem. The data in these tables are arranged so that they are rapidly accessible to the Monte Carlo tracking routines.

Table 1

There is an entry in Table 1 corresponding to each region of the problem. (The i^{th} entry corresponds to the i^{th} region.) Each entry to Table 1 is packed into 35 bits as follows.

1. The first three high order bits contain the number of internal regions that the region sees (see Section 6.1). The maximum number of such regions for any given region is seven.
2. The next three bits describe the type of region
 - 0 = ordinary parallelepiped
 - 1 = sphere
 - 2 = cylinder
 - 3 = wedge
 - 4 = nonordinary parallelepiped
 - 5 = frusta of cone.
3. The next eight bits contain the number of the region external to the region. This only applies to nonordinary regions, types 1-5).
4. The next seven bits contain a location relative to Table 2 where the regions whose external region is the region considered are listed. The entry is zero when there are no such regions.

5. The last 14 bits contain the location relative to Table 3 where the region data are listed.

Table 2

This table contains an entry for each of the nonordinary regions (types 1-5), and these entries are grouped corresponding to their external region. Each entry is packed into 25 bits as follows.

1. The first three bits contain the type of the region (same as Table 1, item 2 but 0 type is excluded).
2. The next eight bits contain the region number of the nonordinary region.
3. The next 14 bits contain the location relative to Table 3 where the region data are listed.

Table 3

This table contains the parameters that define each region. The first location is referenced from Table 1 or Table 2.

1. Ordinary Parallelepipeds

The first six entries contain the six bounding planes ($x_i^\alpha, x_i^\beta, i = 1, 2, 3$). The next six entries contain the adjacent region numbers for each of the corresponding six sides.

- a. If a side sees more than one region this side is defined as a complex surface. The entry contains the negative of the location relative to Table 3 where the data for the complex surface may be found. At this location relative to Table 3 the following information is recorded:
 - (1) A word containing the number of horizontal and the number of vertical intervals for the complex surface packed 18 bits apart.
 - (2) Following this word appear the upper limit of each of the horizontal intervals.

- (3) Then the upper limits of each of the vertical intervals appear.
 - (4) Finally, packed four to a word, nine bits apart, are the regions on the complex surface. The region numbers along the horizontal, from the first to the last horizontal interval are listed for the first vertical interval; then for the second vertical interval, etc. as shown in Fig. 6.
- b. If the side sees only one region then the region number of this region appears.

2. Nonordinary Regions (Types 1-5)

a. Spheres

The first three entries contain the coordinates of the center of the sphere. The next entry is the square of the sphere radius.

b. Cylinders

The first three entries contain the coordinates of the center of the base. The next entry contains the square of the base radius. The next three entries contain the x-y-z components of the height vector of the cylinder.

c. Nonordinary Parallelepipeds

The first three entries contain the coordinates of the vertex of the parallelepiped. The next nine entries contain the x-y-z components of the three vectors which define the parallelepiped.

c. Wedges

The description for the wedge is the same as the nonordinary parallelepiped, the two first vectors defining the legs of the wedge right triangle.

e. Right Frusta of Cones

The first three entries contain the coordinates of the center of the lower base. The next two entries contain the square of the radii of the

lower and upper bases respectively. The following three entries contain the x-y-z components of the height vector.

6.3.3 Input Sheets for EZGEOM

Input sheets for EZGEOM are shown on the following pages.

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EZGEO INPUT

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FZGEOM TITLE CARD									
<p style="text-align: center;">Descriptive title, can be alphabetic and numeric</p> <p style="text-align: right;">Card I.D. No.</p>									

Descriptive title, can be alphabetic and numeric

Card I.D. No.

177 78 79 80
178 79 80
179 80
180

PROBLEM INFORMATION CARD

Number of ordin. 1' rectangular parallelepipeds, M	Number of non-ordinary regions, N	Card I.D. No.
1	1	EZGEOOM2
2	2	131415161718191A1B1C1D1E1F1G1H1I1J1K1L1M1N1O1P1Q1R1S1T1U1V1W1X1Y1Z1
3	3	2122232425262728292A2B2C2D2E2F2G2H2I2J2K2L2M2N2O2P2Q2R2S2T2U2V2W2X2Y2Z2
4	4	3132333435363738393A3B3C3D3E3F3G3H3I3J3K3L3M3N3O3P3Q3R3S3T3U3V3W3X3Y3Z3
5	5	4142434445464748494A4B4C4D4E4F4G4H4I4J4K4L4M4N4O4P4Q4R4S4T4U4V4W4X4Y4Z4
6	6	5152535455565758595A5B5C5D5E5F5G5H5I5J5K5L5M5N5O5P5Q5R5S5T5U5V5W5X5Y5Z5
7	7	6162636465666768696A6B6C6D6E6F6G6H6I6J6K6L6M6N6O6P6Q6R6S6T6U6V6W6X6Y6Z6
8	8	7172737475767778797A7B7C7D7E7F7G7H7I7J7K7L7M7N7O7P7Q7R7S7T7U7V7W7X7Y7Z7
9	9	8182838485868788898A8B8C8D8E8F8G8H8I8J8K8L8M8N8O8P8Q8R8S8T8U8V8W8X8Y8Z8
10	10	9192939495969798999A9B9C9D9E9F9G9H9I9J9K9L9M9N9O9P9Q9R9S9T9U9V9W9X9Y9Z9
11	11	101112131415161718191A1B1C1D1E1F1G1H1I1J1K1L1M1N1O1P1Q1R1S1T1U1V1W1X1Y1Z1
12	12	1112131415161718191A1B1C1D1E1F1G1H1I1J1K1L1M1N1O1P1Q1R1S1T1U1V1W1X1Y1Z1
13	13	12131415161718191A1B1C1D1E1F1G1H1I1J1K1L1M1N1O1P1Q1R1S1T1U1V1W1X1Y1Z1
14	14	131415161718191A1B1C1D1E1F1G1H1I1J1K1L1M1N1O1P1Q1R1S1T1U1V1W1X1Y1Z1
15	15	1415161718191A1B1C1D1E1F1G1H1I1J1K1L1M1N1O1P1Q1R1S1T1U1V1W1X1Y1Z1
16	16	15161718191A1B1C1D1E1F1G1H1I1J1K1L1M1N1O1P1Q1R1S1T1U1V1W1X1Y1Z1
17	17	161718191A1B1C1D1E1F1G1H1I1J1K1L1M1N1O1P1Q1R1S1T1U1V1W1X1Y1Z1
18	18	1718191A1B1C1D1E1F1G1H1I1J1K1L1M1N1O1P1Q1R1S1T1U1V1W1X1Y1Z1
19	19	18191A1B1C1D1E1F1G1H1I1J1K1L1M1N1O1P1Q1R1S1T1U1V1W1X1Y1Z1
20	20	191A1B1C1D1E1F1G1H1I1J1K1L1M1N1O1P1Q1R1S1T1U1V1W1X1Y1Z1

Note: M+N = 200
N = 12?

BOUNDRY PLANE CARDS FOR ORDINARY RECTANGULAR PARALLEL PIPELINES (ONE CARD PER REGION)

•This number should be the number of the pertinent region.

SPHERICAL GEOMETRY INPUT (ONE CARD PER SPHERE)			Radius of sphere	Number of the region that is external to sphere	Region number of sphere
X coordinate of center of sphere	Y coordinate of center of sphere	Z coordinate of center of sphere			
1.2	1.3	1.4	37	33	1.1
1.1	1.2	1.3	38	34	1.2
1.0	1.1	1.2	39	35	1.3
0.9	1.0	1.1	40	36	1.4
0.8	0.9	1.0	41	37	1.5
0.7	0.8	0.9	42	38	1.6
0.6	0.7	0.8	43	39	1.7
0.5	0.6	0.7	44	40	1.8
0.4	0.5	0.6	45	41	1.9
0.3	0.4	0.5	46	42	1.10
0.2	0.3	0.4	47	43	1.11
0.1	0.2	0.3	48	44	1.12
0.0	0.1	0.2	49	45	1.13
-0.1	0.0	0.1	50	46	1.14
-0.2	-0.1	0.0	51	47	1.15
-0.3	0.0	-0.1	52	48	1.16
-0.4	0.1	-0.2	53	49	1.17
-0.5	0.2	-0.3	54	50	1.18
-0.6	0.3	-0.4	55	51	1.19
-0.7	0.4	-0.5	56	52	1.20
-0.8	0.5	-0.6	57	53	1.21
-0.9	0.6	-0.7	58	54	1.22
-1.0	0.7	-0.8	59	55	1.23
-1.1	0.8	-0.9	60	56	1.24
-1.2	0.9	-1.0	61	57	1.25
-1.3	1.0	-1.1	62	58	1.26
-1.4	1.1	-1.2	63	59	1.27
-1.5	1.2	-1.3	64	60	1.28
-1.6	1.3	-1.4	65	61	1.29
-1.7	1.4	-1.5	66	62	1.30
-1.8	1.5	-1.6	67	63	1.31
-1.9	1.6	-1.7	68	64	1.32
-2.0	1.7	-1.8	69	65	1.33
-2.1	1.8	-1.9	70	66	1.34
-2.2	1.9	-2.0	71	67	1.35
-2.3	2.0	-2.1	72	68	1.36
-2.4	2.1	-2.2	73	69	1.37
-2.5	2.2	-2.3	74	70	1.38
-2.6	2.3	-2.4	75	71	1.39
-2.7	2.4	-2.5	76	72	1.40
-2.8	2.5	-2.6	77	73	1.41
-2.9	2.6	-2.7	78	74	1.42
-3.0	2.7	-2.8	79	75	1.43
-3.1	2.8	-2.9	80	76	1.44
-3.2	2.9	-3.0	81	77	1.45
-3.3	3.0	-3.1	82	78	1.46
-3.4	3.1	-3.2	83	79	1.47
-3.5	3.2	-3.3	84	80	1.48
-3.6	3.3	-3.4	85	81	1.49
-3.7	3.4	-3.5	86	82	1.50
-3.8	3.5	-3.6	87	83	1.51
-3.9	3.6	-3.7	88	84	1.52
-4.0	3.7	-3.8	89	85	1.53
-4.1	3.8	-3.9	90	86	1.54
-4.2	3.9	-4.0	91	87	1.55
-4.3	4.0	-4.1	92	88	1.56
-4.4	4.1	-4.2	93	89	1.57
-4.5	4.2	-4.3	94	90	1.58
-4.6	4.3	-4.4	95	91	1.59
-4.7	4.4	-4.5	96	92	1.60
-4.8	4.5	-4.6	97	93	1.61
-4.9	4.6	-4.7	98	94	1.62
-5.0	4.7	-4.8	99	95	1.63
-5.1	4.8	-4.9	100	96	1.64
-5.2	4.9	-5.0	101	97	1.65
-5.3	5.0	-5.1	102	98	1.66
-5.4	5.1	-5.2	103	99	1.67
-5.5	5.2	-5.3	104	100	1.68
-5.6	5.3	-5.4	105	101	1.69
-5.7	5.4	-5.5	106	102	1.70
-5.8	5.5	-5.6	107	103	1.71
-5.9	5.6	-5.7	108	104	1.72
-6.0	5.7	-5.8	109	105	1.73
-6.1	5.8	-5.9	110	106	1.74
-6.2	5.9	-6.0	111	107	1.75
-6.3	6.0	-6.1	112	108	1.76
-6.4	6.1	-6.2	113	109	1.77
-6.5	6.2	-6.3	114	110	1.78
-6.6	6.3	-6.4	115	111	1.79
-6.7	6.4	-6.5	116	112	1.80
-6.8	6.5	-6.6	117	113	1.81
-6.9	6.6	-6.7	118	114	1.82
-7.0	6.7	-6.8	119	115	1.83
-7.1	6.8	-6.9	120	116	1.84
-7.2	6.9	-7.0	121	117	1.85
-7.3	7.0	-7.1	122	118	1.86
-7.4	7.1	-7.2	123	119	1.87
-7.5	7.2	-7.3	124	120	1.88
-7.6	7.3	-7.4	125	121	1.89
-7.7	7.4	-7.5	126	122	1.90
-7.8	7.5	-7.6	127	123	1.91
-7.9	7.6	-7.7	128	124	1.92
-8.0	7.7	-7.8	129	125	1.93
-8.1	7.8	-7.9	130	126	1.94
-8.2	7.9	-8.0	131	127	1.95
-8.3	8.0	-8.1	132	128	1.96
-8.4	8.1	-8.2	133	129	1.97
-8.5	8.2	-8.3	134	130	1.98
-8.6	8.3	-8.4	135	131	1.99
-8.7	8.4	-8.5	136	132	2.00
-8.8	8.5	-8.6	137	133	2.01
-8.9	8.6	-8.7	138	134	2.02
-9.0	8.7	-8.8	139	135	2.03
-9.1	8.8	-8.9	140	136	2.04
-9.2	8.9	-9.0	141	137	2.05
-9.3	9.0	-9.1	142	138	2.06
-9.4	9.1	-9.2	143	139	2.07
-9.5	9.2	-9.3	144	140	2.08
-9.6	9.3	-9.4	145	141	2.09
-9.7	9.4	-9.5	146	142	2.10
-9.8	9.5	-9.6	147	143	2.11
-9.9	9.6	-9.7	148	144	2.12
-10.0	9.7	-9.8	149	145	2.13
-10.1	9.8	-9.9	150	146	2.14
-10.2	9.9	-10.0	151	147	2.15
-10.3	10.0	-10.1	152	148	2.16
-10.4	10.1	-10.2	153	149	2.17
-10.5	10.2	-10.3	154	150	2.18
-10.6	10.3	-10.4	155	151	2.19
-10.7	10.4	-10.5	156	152	2.20
-10.8	10.5	-10.6	157	153	2.21
-10.9	10.6	-10.7	158	154	2.22
-11.0	10.7	-10.8	159	155	2.23
-11.1	10.8	-10.9	160	156	2.24
-11.2	10.9	-11.0	161	157	2.25
-11.3	11.0	-11.1	162	158	2.26
-11.4	11.1	-11.2	163	159	2.27
-11.5	11.2	-11.3	164	160	2.28
-11.6	11.3	-11.4	165	161	2.29
-11.7	11.4	-11.5	166	162	2.30
-11.8	11.5	-11.6	167	163	2.31
-11.9	11.6	-11.7	168	164	2.32
-12.0	11.7	-11.8	169	165	2.33
-12.1	11.8	-11.9	170	166	2.34
-12.2	11.9	-12.0	171	167	2.35
-12.3	12.0	-12.1	172	168	2.36
-12.4	12.1	-12.2	173	169	2.37
-12.5	12.2	-12.3	174	170	2.38
-12.6	12.3	-12.4	175	171	2.39
-12.7	12.4	-12.5	176	172	2.40
-12.8	12.5	-12.6	177	173	2.41
-12.9	12.6	-12.7	178	174	2.42
-13.0	12.7	-12.8	179	175	2.43
-13.1	12.8	-12.9	180	176	2.44
-13.2	12.9	-13.0	181	177	2.45
-13.3	13.0	-13.1	182	178	2.46
-13.4	13.1	-13.2	183	179	2.47
-13.5	13.2	-13.3	184	180	2.48
-13.6	13.3	-13.4	185	181	2.49
-13.7	13.4	-13.5	186	182	2.50
-13.8	13.5	-13.6	187	183	2.51
-13.9	13.6	-13.7	188	184	2.52
-14.0	13.7	-13.8	189	185	2.53
-14.1	13.8	-13.9	190	186	2.54
-14.2	13.9	-14.0	191	187	2.55
-14.3	14.0	-14.1	192	188	2.56
-14.4	14.1	-14.2	193	189	2.57
-14.5	14.2	-14.3	194	190	2.58
-14.6	14.3	-14.4	195	191	2.59
-14.7	14.4	-14.5	196	192	2.60
-14.8	14.5	-14.6	197	193	2.61
-14.9	14.6	-14.7	198	194	2.62
-15.0	14.7	-14.8	199	195	2.63
-15.1	14.8	-14.9	200	196	2.64
-15.2	14.9	-15.0	201	197	2.65
-15.3	15.0	-15.1	202	198	2.66
-15.4	15.1	-15.2	203	199	2.67
-15.5	15.2	-15.3	204	200	2.68
-15.6	15.3	-15.4	205	201	2.69
-15.7	15.4	-15.5	206	202	2.70
-15.8	15.5	-15.6	207	203	2.71
-15.9	15.6	-15.7	208	204	2.72
-16.0	15.7	-15.8	209	205	2.73
-16.1	15.8	-15.9	210	206	2.74
-16.2	15.9	-16.0	211	207	2.75
-16.3	16.0	-16.1	212	208	2.76
-16.4	16.1	-16.2	213	209	2.77
-16.5	16.2	-16.3	214	210	2.78
-16.6	16.3	-16.4	215	211	2.79
-16.7	16.4	-16.5	216	212	2.80
-16.8	16.5	-16.6	217	213	2.81
-16.9	16.6	-16.7	218	214	2.82
-17.0	16.7	-16.8	219	215	2.83
-17.1	16.8	-16.9	220	216	2.84
-17.2	16.9	-17.0	221	217	2.85
-17.3	17.0	-17.1	222	218	2.86
-17.4	17.1	-17.2	223	219	2.87
-17.5	17.2	-17.3	224	220	2.88
-17.6	17.3	-17.4	225	221	2.89
-17.7	17.4	-17.5	226	222	2.90
-17.8	17.5	-17.6	227	223	2.91
-17.9	17.6	-17.7	228	224	2.92
-18.0	17.7	-17.8	229	225	2.93
-18.1	17.8	-17.9	230	226	2.94
-18.2	17.9	-18.0	231	227	2.95
-18.3	18.0	-18.1	232	228	2.96
-18.4	18.1	-18.2	233	229	2.97
-18.5	18.2	-18.3	234	230	2.98
-18.6	18.3	-18.4	235	231	2.99
-18.7	18.4	-18.5	236	232	3.00

EXCEDEON INPUT (CONTINUED)

CYLINDRICAL GEOMETRY INPUT (CARD 1)			Radius of base of cylinder	Number of the region that is external to cylinder	Region number of cylinder
X coordinate of center of base of cylinder	Y coordinate of center of base of cylinder	Z coordinate of center of base of cylinder			
1.2	1.5	1.8	1.9	1.0	1.1
1.5	1.8	2.1	2.2	2.3	2.4
1.8	2.1	2.4	2.7	2.8	2.9
2.1	2.4	2.7	3.0	3.1	3.2
2.4	2.7	3.0	3.3	3.4	3.5
2.7	3.0	3.3	3.6	3.7	3.8
3.0	3.3	3.6	3.9	4.0	4.1
3.3	3.6	3.9	4.2	4.3	4.4
3.6	3.9	4.2	4.5	4.6	4.7
3.9	4.2	4.5	4.8	4.9	5.0
4.2	4.5	4.8	5.1	5.2	5.3
4.5	4.8	5.1	5.4	5.5	5.6
4.8	5.1	5.4	5.7	5.8	5.9
5.1	5.4	5.7	6.0	6.1	6.2
5.4	5.7	6.0	6.3	6.4	6.5
5.7	6.0	6.3	6.6	6.7	6.8
6.0	6.3	6.6	6.9	7.0	7.1
6.3	6.6	6.9	7.2	7.3	7.4
6.6	6.9	7.2	7.5	7.6	7.7
6.9	7.2	7.5	7.8	7.9	8.0

Repeat above 5 cards for each cylinder

EZGEOM INPUT (CONTINUED)

WEDGE GEOMETRY INPUT (CARD 1)		
X coordinate of vertex of wedge	Y coordinate of vertex of wedge	Z coordinate of vertex of wedge
1 2 3 4 5 6 7 8 9 10 11 12	13 14 15 16 17 18 19 20 21 22 23 24	25 26 27 28 29 30 31 32 33 34 35 36

E₁ E₂ E₃ E₄ E₅ E₆ E₇ E₈ E₉ E₁₀ E₁₁ E₁₂

WEDGE GEOMETRY INPUT (CARD 1)		
X coordinate of vertex of wedge	Y coordinate of vertex of wedge	Z coordinate of vertex of wedge
1 2 3 4 5 6 7 8 9 10 11 12	13 14 15 16 17 18 19 20 21 22 23 24	25 26 27 28 29 30 31 32 33 34 35 36

E₁ E₂ E₃ E₄ E₅ E₆ E₇ E₈ E₉ E₁₀ E₁₁ E₁₂

WEDGE GEOMETRY INPUT (CARD 2) *		
X component of first base vector	Y component of first base vector	Z component of first base vector
1 2 3 4 5 6 7 8 9 10 11 12	13 14 15 16 17 18 19 20 21 22 23 24	25 26 27 28 29 30 31 32 33 34 35 36

E₁ E₂ E₃ E₄ E₅ E₆ E₇ E₈ E₉ E₁₀ E₁₁ E₁₂

WEDGE GEOMETRY INPUT (CARD 2) *		
X component of first base vector	Y component of first base vector	Z component of first base vector
1 2 3 4 5 6 7 8 9 10 11 12	13 14 15 16 17 18 19 20 21 22 23 24	25 26 27 28 29 30 31 32 33 34 35 36

E₁ E₂ E₃ E₄ E₅ E₆ E₇ E₈ E₉ E₁₀ E₁₁ E₁₂

WEDGE GEOMETRY INPUT (CARD 3)		
X component of the length vector of wedge	Y component of the length vector of wedge	Z component of the length vector of wedge
1 2 3 4 5 6 7 8 9 10 11 12	13 14 15 16 17 18 19 20 21 22 23 24	25 26 27 28 29 30 31 32 33 34 35 36

E₁ E₂ E₃ E₄ E₅ E₆ E₇ E₈ E₉ E₁₀ E₁₁ E₁₂

WEDGE GEOMETRY INPUT (CARD 3)		
X component of the length vector of wedge	Y component of the length vector of wedge	Z component of the length vector of wedge
1 2 3 4 5 6 7 8 9 10 11 12	13 14 15 16 17 18 19 20 21 22 23 24	25 26 27 28 29 30 31 32 33 34 35 36

E₁ E₂ E₃ E₄ E₅ E₆ E₇ E₈ E₉ E₁₀ E₁₁ E₁₂

*See Section 6.1

Repeat above 3 cards for each wedge

NON-ORDINARY RECTANGULAR PARALLELEPIPED GEOMETRY INPUT (CARD 1)

X coordinate of vertex	Y coordinate of vertex	Z coordinate of vertex	Number of region that is external to the region	Region number
1 2 3 4 5 6 7 8 9 10 11 12 ●	1 2 3 4 5 6 7 8 9 10 11 12 ●	1 2 3 4 5 6 7 8 9 10 11 12 ●	25 26 27 28 29 30 31 32 33 34 35 36 ●	33 34 35 36 37 38 39 40 41 42 43 44 R, P, P

NON-ORDINARY RECTANGULAR PARALLELEPIPED GEOMETRY INPUT (CARD 2)

X component of first base vector	Y component of first base vector	Z component of first base vector	X component of second base vector	Y component of second base vector	Z component of second base vector	Number of region that is external to the region	Region number
1 2 3 4 5 6 7 8 9 10 11 12 ●	1 2 3 4 5 6 7 8 9 10 11 12 ●	1 2 3 4 5 6 7 8 9 10 11 12 ●	25 26 27 28 29 30 31 32 33 34 35 36 ●	37 38 39 40 41 42 43 44 45 46 47 48 ●	49 50 51 52 53 54 55 56 57 58 59 60 ●	61 62 63 64 65 66 67 68 69 70 71 72 ●	73 74 75 76 77 78 79 70 71 72 73 74 R, P, P

NON-ORDINARY RECTANGULAR PARALLELEPIPED GEOMETRY INPUT (CARD 3)

X component of the length vector	Y component of the length vector	Z component of the length vector	Number of region that is external to the region	Region number
1 2 3 4 5 6 7 8 9 10 11 12 ●	1 2 3 4 5 6 7 8 9 10 11 12 ●	1 2 3 4 5 6 7 8 9 10 11 12 ●	25 26 27 28 29 30 31 32 33 34 35 36 ●	47 48 49 50 51 52 53 54 55 56 57 58 ●

Repeat above 3 cards for each non-ordinary rectangular parallelepiped

EIGENCOM INPUT (CONTINUED)

Page 7 of 7

Repeat above 2 cards for each frustum

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7. THE TRACKING AND SCORING MONTE CARLO PROGRAM – ADONIS

Having appropriate output tapes of DATORG, VANGEN or GASP, and EZGEOM, we are ready to proceed with the transport game⁷ for the solution of the Boltzmann integral equations. The transport game is basically an analog of the physical transport of a neutron or a gamma ray. However, in most problems, it is necessary to modify the game to obtain the desired result efficiently.

At each event to be considered in the game, a weight is introduced. The purpose of carrying along the weight is to enable the consideration of altered games of chance which lead to appreciable variance reductions. At the present time, the ADONIS program employs two methods of variance reduction: importance sampling, and statistical estimations in the special case of flux evaluation in small detector regions.

As the transport game is played, a variety of information, including the following, is recorded.

1. The average flux as a function of energy group in each ordinary and non-ordinary region along with its standard deviation. If any quantity proportional to the flux is desired, it can be computed using appropriate response functions.
2. A neutron interaction tape for future secondary source emission processing .

3. A tape containing information on transmitted particles for future processing.
4. The number of absorptions per element and per region, births and deaths due to importance sampling in each region, and energy degradations below an optional energy cutoff.
5. The average flux as a function of energy at specified detector points along with its standard deviation (optional, for neutron problems only).

We turn our attention to the description of the transport game played by ADONIS.

7.1 THE TRACKING PROCESS

The ADONIS program uses the source particle tape created by VANGEN, GASP, or a similar source generator program to start particle histories. The position, \underline{P} , the energy, E, and the direction, $\underline{\Omega}$, of the source particle, and R_i , the region in which the particle is born, are read off the tape.

The first problem that must be solved is to determine the position of the next collision and the region in which that collision will occur. It can be shown that the number of mean free paths, λ , that a neutron is to travel before interacting must be selected from a probability distribution function $e^{-\lambda}$ (using the definition of the transport kernel in the Boltzmann integral equation). Then, the distance from \underline{P} along $\underline{\Omega}$ to the first collision location \underline{P}' is given by

$$\lambda = \sum_{k=i}^{\eta} \mu_T(E, R_k) S_k = 0 \quad (55)$$

where $\mu_T(E, R_k)$ = the total cross section at energy E of the composition in region R_k

S_k = the distance along the particle flight path in region R_k .

$R_i, R_{i+1}, \dots, R_k, \dots, R_\eta$ are the regions which are seen successively along the flight path.

Further, it can be shown that, if ξ is a random number in the interval (0, 1), the probability distribution for $-\ln \xi$ is $e^{-\lambda}$.

Therefore,

$$\lambda = -\ln \xi \quad (56)$$

The techniques used by the ADONIS program to solve the problem now can be discussed.

1. A random number, ξ , is selected using the subroutine RANDM. This subroutine is written in FORTRAN language and generates equi-distributed pseudorandom numbers on the interval (0, 1) compatible with the word length of the computing machine used. For the CDC-1604-A, the period of the random number sequence is $X_0 = 5^{13}$ and the starting number is usually an odd prime number. The successor, ξ_{n+1} , of a random number, ξ_n , is obtained by taking the product $X_0 \xi_n$, rejecting the first half of the significant figures of the product and floating the remainder.
2. The number of mean free paths λ is computed using Eq. 56.
3. The cross section $\mu_T(E, R_i)$ of the composition in the region where the particle is born is computed by linear interpolation of the cross sections generated by DATORG at the output energies defined in the GENDA routine. The subroutine Data Retrieval, entry 1 (DR,1) computes the interpolation factor, f . The subroutine Data Retrieval, entry 2 (DR,2) computes $\mu_T(E, R_i)$ using the interpolation factor obtained from (DR,1) and the table of total cross sections for the composition in R_i . Note that in going through regions containing different compositions without change in particle energy, only (DR,2) is called since the interpolation factor is unchanged.
4. Given the location P and the direction Ω in a given region, R_i , the subroutine Geometry 1 (G1) determines how far it is to the next region and

what surface the particle will cross if it does travel that far, using the geometry tables created by EZGEOM (Section 6) and special routines for each type of region, G1 (TYP), where TYP = ORP, SPH, CYL, WED, RPP. These denote ordinary region, sphere, cylinder, wedge, or non-ordinary parallelepiped, respectively.

The number of regions, m_B , wholly contained in a given region R_i is obtained from Table 1.

If $m_B = 0$, G1(TYP) and R_i determine S_i . The intersection \underline{P}' of the flight path with the appropriate edge of R_i is computed* and

$$S_i = |\underline{P}' - \underline{P}|.$$

If $m_B \neq 0$, G1 determines whether or not the flight path intersects each of the m_B regions enumerated in Table 2 using G1(TYP). If there is no intersection with any of these regions, the procedure is similar to the case $m_B = 0$. If there are one or more intersections, the distances from P to the intersection points are computed and the shortest distance is then retained.

5. The next task is to determine whether or not the particle makes a collision before traveling the distance S_i .

If $\lambda - \mu_T(E, R_i) S_i > 0$, the particle does cross into the next region. A subroutine called Geometry 2 (G2) is now used to determine the region, R_{i+1} , and the particle enters using the information gathered in Tables 2, 3, and G1. Then the remaining number of mean free paths is determined by replacing λ by

$$\lambda' = \lambda - \mu_T(E, R_i) S_i \quad (57)$$

and the procedure is repeated by computing $\mu_T(E, R_{i+1})$ and going to G1. In other

*The method used in these computations has been described in unpublished memos by J. Certaine.^{8,9,10}

words, the particle is tracked into the next region. There are, however, two important tests that are performed before tracking in the next region is started. First, the program determines whether the region in which the particle enters is a reflecting or transmitting region.*

If this is the case, the tracking of the particle is terminated and the proper reflecting or transmitting counters are updated.

If the region is neither reflecting nor transmitting, a second test is performed. As pointed out above, the consideration of variance reduction techniques may lead to the introduction of weighting functions which are position and energy dependent.

At the present time, ADONIS considers weighting functions piecewise constant in each region and in given energy intervals, $W(E,R)$ (Section 7.3.1). The program compares the ratio of weights at energy E in region R_i and R_{i+1} .

*It is necessary to terminate the particle tracking upon leaving the environment of the geometrical configuration of interest. Three devices have been built into the program to handle this situation.

1. If the "importance" of a particle in a particular region is made sufficiently low, the particle entering that region will be killed (see Section 7.3).
2. If a fictitious macroscopic absorption cross section sufficiently large is attached to a given region, incident particles will be absorbed.
3. A very rapid way to terminate particle tracking is accomplished by the introduction of two special types of regions: the reflecting region (required to be region 1) and the transmitting region (which can be any region) which have the following properties:
 - a. Particles incident on both regions are terminated and counted separately.
 - b. For transmitted particles only, the location at which the particle path flight enters the region, the energy, the direction, and the original history number of the particle and the region from which the particle has come are recorded on a tape in the same order as specified for the source tape (Section 5).

$$\frac{W(E, R_i)}{W(E, R_{i+1})} = N + F \quad (58)$$

where N and F are the integral and fractional portions of the quotient, respectively.

A random number ξ is selected and compared to F ; then, if $\xi < F$, N is replaced by $N+1$. If $\xi > F$, N is left unchanged. N is by definition the number of particles created. If $N = 0$, the tracking is terminated and the counter registering the number of deaths by importance sampling is increased by 1. If $N = 1$, no additional particle has been created and the tracking of the particle is continued. Note that if $W(E, R) = 1$ for all E and R , this means that the transport game is modeled directly after the physical problem of particle transport. If $N > 1$, the phase-space coordinates of the $N-1$ additional particles are put into a table along with the number $N-1$. This entry in the table is defined as $(N-1)$ latent particles. The tracking is continued with the N^{th} particle. When tracking of a particle is terminated, the program searches the latent table, picks the last latent particle entered and starts tracking it. The particle history is terminated when tracking of the original particle and all the latent particles is completed.

The region in which the particle makes a collision is determined as follows. Starting from region R_i , the above procedure is continued until it is found that in some region R_k

$$\lambda - \mu_T(E, R_k) S_k < 0 \quad (59)$$

The program then proceeds to bring the particle to the collision point in R_k . Indeed, the distance from the edge of region R_k to the collision point is given by $\lambda / \mu_T(E, R_k)$.

We must now determine with which element in the region R_k the particle collides, the type of collision, and the energy and direction of the emerging particle, if

any. This is obtained by the interaction routines which are described in Section 7.2.

The tracking of the particle coming out of collision is resumed by choosing a new λ and repeating the process described above.

7.2 THE INTERACTION ROUTINES

The interaction experienced by the particle is determined in two steps. First the interacting element is chosen; second, the specific event is chosen. If the event is scattering, the energy and direction of the scattered particle are evaluated.

The interacting element is chosen by comparing the product of a random number with the total macroscopic cross section of the region composition, $\xi \mu_T(E, R)$, with the total macroscopic cross section of each element in that composition, $\mu_T(E, e_j)$, where e_j denotes the j^{th} element in the composition of region R , $j = 1, 2, \dots, \ell, \dots, L$. If

$$\sum_{j=1}^{\ell-1} \mu_T(E, e_j) < \xi \mu_T(E, R) < \sum_{j=1}^{\ell} \mu_T(E, e_j), \quad (60)$$

then the interacting element is e_ℓ .

The type of interaction is similarly determined by comparing a random number to the probabilities that a given event takes place. These probabilities have been tabulated for each element by the GENPRO routine.

The ADONIS subroutine which is used to select the interacting element and the type of interaction is called Data Retrieval, entry 3 (DR,3).

The incident energy, E , is referenced with respect to the output mesh energies E_j^G in an energy interval (E_j^G, E_{j+1}^G) by (DR,1). For each element, at each E_j^G ,

GENPRO supplies tables of total microscopic cross sections, scattering probabilities, absorption probabilities, and a scattering index. This index gives the type of scattering, if any, e.g., elastic, discrete or continuum inelastic. If elastic scattering is indexed, it gives the type of elastic scattering that the particle suffers. For anisotropic elastic scattering, discrete inelastic, or continuum inelastic scattering, the scattering index gives the proper location of the tables of probabilities supplied by GENPRO: CHI, PLEV, and ENN tables (see Section 3).

(DR,3) compares a random number, ξ , in (0,1) to the probability of scattering at energy E [obtained by interpolation using the f computed by (DR,1)].

If the event is absorption, the number of absorptions in the element and the region are updated, the particle tracking is terminated, and tracking of a latent particle, if any, is started.

If the event is scattering, the energy after scattering, EPRIM, (E'), and the cosine of the angle of scattering in the laboratory system, CSTHT, ($\cos \theta$), are computed by calling the appropriate routines: ELAS and INELAS for neutron elastic and inelastic scattering, respectively, and NIKI for gamma elastic scattering.

ELAS Routine

The control digit NCBD is set to 1, 2, 3, 4 for the following cases: (1) isotropic in center of mass system, (2) hydrogen scatterer, (3) anisotropic scattering, and (4) isotropic in laboratory system - no energy degradation.

1. Isotropic Scattering in Center of Mass System

It can be shown that if ξ is random in (0,1)

$$X = \frac{1 - \cos \theta_C}{2} = \xi \quad (61)$$

where θ_C is the scattering angle in the center of mass system. E' and

$\cos \theta$ are then obtained by the standard relations

$$E' = E \left[1 - \frac{4AX}{(1+A)^2} \right] \quad (62)$$

$$\cos \theta = \frac{A+1-2AX}{(A+1) \left[1 - \frac{4AX}{(A+1)^2} \right]^{1/2}} \quad (63)$$

where A = the element atomic weight

E = the incident energy.

2. Hydrogen Scatterer

Upon collision with hydrogen, particles are scattered in the forward direction only. It can be shown that the probability distribution function $\cos \theta$ is given by $2 \cos \theta$.

To pick a $\cos \theta$ from the distribution $2 \cos \theta$, two random numbers¹¹ are selected and the larger of the two is retained as $\cos \theta$. Then

$$E' = E (\cos \theta)^2 \quad (64)$$

3. Anisotropic Scattering

The cosines of angles between which elastic scattering is equally probable for the specified energy mesh points, E_j^G , are supplied in the CHI tables referenced by the scattering index.

If the incident neutron energy, E , lies in the interval (E_j^G, E_{j+1}^G) , the CHI table relative to E_j^G is selected. This tabulation consists of

$$x_n = \frac{1 - \cos \theta_n}{2} \quad \text{for } n = 0, 1, 2, \dots, N$$

where $x_0 = 0$, $x_N = 1$, $0 \leq x_n \leq 1$.

In ADONIS, N is restricted to 10. The proper χ is selected by choosing a random number, ξ , and comparing the product 10ξ to the numbers 1, 2, ..., N = 10 successively.

Assume that $n < 10\xi < n+1$

This means that $x_n < \chi < x_{n+1}$

The integral part of the product 10ξ is rejected and the remainder is taken as the interpolation factor, f. [This assumes a uniform probability distribution of χ in each interval (x_n, x_{n+1}) .]

Then

$$\chi = x_n + f(x_{n+1} - x_n) \quad (65)$$

This function is performed by the Data Retrieval, entry 6 routine (DR,6).

Therefore,

$$\cos \theta = 1 - 2\chi \quad (66)$$

and E' is obtained using Eq. 52.

4. Isotropic in Laboratory System – No Degradation

If the scatterer atomic weight is large, Eqs. 62 and 63 show that

$$E' \approx E \quad (67)$$

$$\cos \theta \approx 1 - 2\chi = \cos \theta_c \quad (68)$$

Thus, the scattering is approximately isotropic in the laboratory system and the particle energy remains unchanged by the collision. Therefore, a random number, ξ , is chosen and $\cos \theta = 1 - 2\xi$.

INELAS Routine

Data Retrieval, entries 7 and 8 subroutines, (DR,7) and (DR,8) are entered for discrete and continuum scattering, respectively (overlapping is included in the continuum spectrum), to select E' .

If E lies in (E_j^G, E_{j+1}^G) , the PLEV and ELEV tables* for discrete scattering or the ENN table* for continuum scattering relative to E_j^G are selected.

To select from the ENN table, (DR,8) uses the same technique as (DR,6).

To select from the PLEV table, (DR,7) uses the same technique as (DR,3) in the selection of the interacting element.

Using the inequality (Expression 60) in which the element e_j is replaced by the energy levels, one obtains the appropriate energy level E^ν to which the particle scatters and $E' = E - E^\nu$.

The NIKI Routine

It is assumed that γ -scattering results from the Compton effect. A γ -ray of energy α (in mc^2) traversing matter has a probability, $p(\chi/\alpha) d\chi d\ell$, of having a collision in the distance $d\ell$ and emerging from this collision with an energy $\alpha' = \chi\alpha$. For χ satisfying $1 \leq \chi \leq 1 + 2\alpha$,

$$p(\chi/\alpha) d\chi = \frac{A}{\chi^2} (\cos^2 \theta - 1 + \chi + \frac{1}{\chi}) d\chi, \quad (69)$$

where $A = n\pi\alpha_0^2/\alpha$

n = the number of electrons per cm^2

α_0 = the classical radius of the electron

θ = the scattering angle which is related to α and χ by the Compton relation

*See Section 3.

$$\cos \theta = \frac{1}{\alpha} - \frac{\chi}{\alpha} + 1. \quad (70)$$

$p(\chi/\alpha)$ is called the Klein-Nishina probability distribution function. To pick a χ from $p(\chi/\alpha)$, a rejection technique devised by H. Kahn is used in ADONIS.¹¹ $p(\chi/\alpha)$ is broken up into the sum of two probability distribution functions. A random number, ξ_1 , is compared to $(2\alpha+1)/(2\alpha+9)$.

If $\xi_1 < (2\alpha+1)/(2\alpha+9)$, y is set equal to $1 + 2\alpha\xi_2$ (where ξ_2 is a second random number), and another random number, ξ_3 , is compared to $4 [(1/y) - (1/y^2)] = m$.

If it is less than m , $\chi = y$. If it is greater than m , y is rejected and the procedure is repeated.

If $\xi_1 > (2\alpha+1)/(2\alpha+9)$, y is set equal to $(2\alpha+1)/(1+2\alpha\xi_2)$, and ξ_3 is compared to

$$\frac{1}{2} \left(\cos^2 \theta + \frac{1}{y} \right),$$

where

$$\cos \theta = \frac{1}{\alpha} - \frac{y}{\alpha} + 1.$$

If it is less than $(1/2) [\cos^2 \theta + (1+y)]$, $\chi = y$. If it is greater than $(1/2)[\cos^2 \theta + (1/y)]$, y is rejected and the procedure is repeated.

Once χ has been selected, NIKI proceeds to compute E' and $\cos \theta$.

The interaction routines compute and transmit to the main program the energy after scattering, E' , and the cosine of the scattering angle, $\cos \theta$. What is required is to evaluate the direction cosines of the new particle direction in the Cartesian coordinate system, given $\cos \theta$ and the initial direction cosines. The DIREC routine computes these angle cosines by means of two subroutines:

1. Subroutine PHI uses a rejection technique to choose the cosine and sine of an azimuthal angle equidistributed in the interval $0 \leq \phi \leq 2\pi$: $\cos \phi$ and $\sin \phi$.
2. Subroutine DCB computes the direction cosines

$$\underline{\Omega}' = (\Omega'_x, \Omega'_y, \Omega'_z) :$$

$$\Omega'_x = \sqrt{\frac{1-\mu^2}{1-\Omega_z^2}} (\Omega_y \cos \phi + \Omega_z \Omega_x \sin \phi) + \Omega_x \mu$$

$$\Omega'_y = \sqrt{\frac{1-\mu^2}{1-\Omega_z^2}} (\Omega_y \Omega_z \sin \phi - \Omega_x \cos \phi) + \Omega_y \mu$$

$$\Omega'_z = \sqrt{(1-\mu^2)(1-\Omega_z^2)} \sin \phi + \Omega_z \mu \quad (71)$$

where $\mu = \cos \theta$;

$\underline{\Omega} = (\Omega_x, \Omega_y, \Omega_z)$ is the given initial direction.

7.3 VARIANCE REDUCTION TECHNIQUES

As pointed out in the introduction to this section, the transport game is altered for better efficiency. In shielding problems, one is interested in particles from a source which are transmitted through the shield. In problems of interest, the transmission is generally small, and, if results with reasonable accuracy are required, an extremely large number of particle histories must be considered. This involves large amounts of computing time; thus it is costly.

To obtain a practical calculation, one must do other than play the direct analog game in which a great deal of time is spent on particles which are not transmitted. Many methods have been tried in which the situation is improved by computing the same average scores but with a reduced variance. Most of these increase the work per game, but hopefully result in a net saving of work. The method of reducing variance in the main program of ADONIS is a particular case of

importance sampling. However, for the special problem of evaluating neutron fluxes in a small volume detector, a different approach is used. Here, instead of decreasing the variance by altering the game, the variance is decreased by changing the method of scoring.¹²⁻¹⁵ This method is called statistical estimations, or scoring by analytical estimations.

7.3.1 ADONIS Importance Sampling

In altering the direct analog game of chance to reduce variance, one tries to estimate the desired result by emphasizing the choice of phase space points which lead to higher expected contribution to the score. $I(\underline{x}, E, \underline{\Omega})$ is a measure of the "importance" of the point $(\underline{x}, E, \underline{\Omega})$.

It can be shown that⁷ the use of $I(\underline{x}, E, \underline{\Omega})$ leads to a game in which particles are picked from an altered source, $\tilde{S}(\underline{x}, E, \underline{\Omega})$, and collision locations and energy and direction of scattered particles are chosen from an altered kernel, $\tilde{K}(\underline{x} \rightarrow \underline{x}'; E \rightarrow E'; \underline{\Omega} \rightarrow \underline{\Omega}')$ such that

$$\tilde{S}(\underline{x}, E, \underline{\Omega}) = \frac{I(\underline{x}, E, \underline{\Omega}) \cdot S(\underline{x}, E, \underline{\Omega})}{\int I(\underline{x}, E, \underline{\Omega}) S(\underline{x}, E, \underline{\Omega}) d\underline{x} dE d\underline{\Omega}} \quad (72)$$

and

$$\tilde{K}(\underline{x} \rightarrow \underline{x}'; E \rightarrow E'; \underline{\Omega} \rightarrow \underline{\Omega}') = \frac{I(\underline{x}, E, \underline{\Omega})}{I(\underline{x}', E, \underline{\Omega}')} K(\underline{x} \rightarrow \underline{x}'; E \rightarrow E'; \underline{\Omega} \rightarrow \underline{\Omega}') \quad (73)$$

where S and K are the normalized source and the collision kernel, respectively, of the integral Boltzmann equation.

The questions are how to choose the most efficient importance function, I , and, having chosen I , how do we play the game of chance?

A proper choice of I forces particles to points in phase space such that their contribution to the desired answer will be large. As a matter of fact, there exists

an ideal importance function which leads to a zero variance game. It can be shown that the most efficient important functions are solutions to the adjoint equations to the Boltzmann equation.¹²⁻¹⁵ Obtaining these solutions presents an equally difficult problem. In practice, the choice of I is limited because it depends on the complexity of the kernel, \tilde{K} . The Boltzmann equation kernel, K , is itself the product of the transport kernel, $T(\underline{x} \rightarrow \underline{x}'; E, \underline{\Omega})$, and the collision kernel, $C(x'; E \rightarrow E'; \underline{\Omega} \rightarrow \underline{\Omega}')$. Hence, we could attach an importance function to each of these kernels separately. The "importance" of a particle will then be governed by the importance of the region in the phase space in which it finds itself at the moment. In ADONIS, the importance function is taken as a piecewise constant function of energy and space and independent of direction angle, i.e., $I(E, \underline{x}) =$ constant in each region R_i and each energy interval, $E_j^G < E < E_{j+1}^G$.

Consider now a particle at energy E leaving collision at \underline{x} in region R_i . When the particle goes from \underline{x} to \underline{x}' , the collision density is changed by the ratio of the importance function at the new point to the importance function at the old point, $[I(E, \underline{x}')]/[I(E, \underline{x})]$. To insure the correct collision density at the new point, we may follow the particle from \underline{x} to \underline{x}' using $T(\underline{x} \rightarrow \underline{x}'; E)$. Having reached the new collision point, create the number $[I(E, \underline{x}')]/[I(E, \underline{x})]$ to go into collision at \underline{x}' . This method assures us of always having the correct collision density since

$$\tilde{T}(\underline{x} \rightarrow \underline{x}'; E, \underline{\Omega}) = \frac{I(E, \underline{x}')}{I(E, \underline{x})} T(\underline{x} \rightarrow \underline{x}'; E, \underline{\Omega}) \quad (74)$$

In ADONIS, a slightly different method is used by considering the region boundaries at which the importance function changes. Suppose that the particle starting from \underline{x} in R_i crosses the boundary between regions R_i and R_{i+1} and that

$$\frac{I(E, R_{i+1})}{I(E, R_i)} = 2.$$

Then the collision density is supposed to double. One way of insuring this is by

creating another particle, precisely like the first, and then following both. Of course, when the particle crosses the boundary from R_{i+1} to R_i , we have to halve it. One way of halving a particle is by "killing" it half the time. The first process is called "particle splitting" and the second process is referred to as "Russian roulette."

Similarly, when the particle enters collision at \underline{x}' , say in region R_k , the "splitting" or the "Russian roulette" technique is used according to the magnitude of the ratio $I(E', R_k)/I(E, R_k)$. We could make the importance function resemble even more closely the true function by including an angular dependence. However, it is no small task to assign, even for simple geometries, an importance function as a function of \underline{x} , E , and Ω in each region.

Note that a weighting function is used in ADONIS. The weight is merely the inverse of the importance, i.e.,

$$W(E, R) = \frac{1}{I(E, R)} \quad (75)$$

When a particle goes from a point $[E, \underline{x}(R_i)]$ to a point $[E', \underline{x}(R_j)]$, we create or kill

$$\frac{W[E, \underline{x}(R_i)]}{W[E', \underline{x}(R_j)]} = \frac{I[E', \underline{x}(R_j)]}{I[E, \underline{x}(R_i)]} \quad (76)$$

particles. The technique used in ADONIS to create or kill particles has been described in Section 7.1.

We now investigate techniques whereby one can get relatively good importance functions.

For the situation in which the importance function is dependent on position only, $I(R)$, it has been shown that it should have the property of keeping the particle flux about constant from one region to the next. What is done in practice is to

run a problem with relatively few histories and see whether the condition is satisfied. If it is not, then we alter the boundaries according to the following criterion. Whenever the number of particles falls off too rapidly, one introduces additional importance boundaries, or increases the value of the importance functions and keeps the boundaries intact. The reverse is done whenever the number of particles increases too rapidly. Some trial and error along with educated guessing can often lead to a good importance function.

When the importance function depends upon energy as well, the same method is used by recording the number of particles created in each energy group for each spatial region.

7.3.2 Scoring by Analytical Estimations – Flux at a Point¹⁶

In some neutron calculations, it is desirable to obtain answers for flux, dose, or the like at a point. Since no history can be expected to carry a neutron through a point, it is necessary to use analytic expected value estimates. The method uses the relation between $\psi(\underline{x}', E, \Omega) d\underline{x}' dE d\Omega$, the density of particles entering collision in volume $d\underline{x}'$ with energy in dE and direction in $d\Omega$, and $\phi(\underline{x})$, the flux at \underline{x} .

$$\phi(\underline{x}) = \int dE' \int d\underline{x}' \int dE \int d\Omega \psi(\underline{x}', E, \Omega) \times \left\{ 2g \left(\frac{\underline{x}-\underline{x}'}{|\underline{x}-\underline{x}'|} \cdot \underline{\Omega}; E \right) \left[\frac{e^{-\mu(E') |\underline{x}-\underline{x}'|}}{4\pi |\underline{x}-\underline{x}'|^2} \right] \right\} \quad (77)$$

where $g(w; E) dw$ = the probability of scattering of a neutron of energy E through an angle whose cosine is in the range $(w, w+dw)$

E' = the energy after scattering

$\mu(E')$ = the total attenuation coefficient of the scattered neutron.

The problem is to evaluate the estimator in brackets in Eq. 77 every time a particle goes into collision and average it over all histories. A straightforward procedure yields an infinite variance if $|x-x'|$ can become very small. Indeed, the estimator has a $|x-x'|^{-2}$ behavior. The method devised by Kalos and employed in ADONIS to avoid infinite variances is to remove the singularity from the scoring function and to incorporate it in the sampling probability distribution function (pdf).

What is required is that for every collision, we estimate the "once-more collided" contribution to the flux at a point and choose the position of the intermediate collision to make the variance finite. Hence, the final estimate is the collided flux only. A separate analytic calculation must be made for the uncollided flux.

If S, D, and A denote the collision point, the detector, and the intermediate point, respectively, and $R = |SD|$, $r_1 = |SA|$, and $r_2 = |AD|$, the following pdf is selected:

$$U_2 dV = \frac{\mu'}{8\pi} \left[\frac{e^{-\mu' r_1}}{r_1^2} + \frac{e^{-\mu' r_2}}{r_2^2} \right] dV \quad (78)$$

where

$$\mu' = \mu(E) + \frac{1}{R} \quad (79)$$

Noting that U_2 is an average of two pdf's, each of the form

$$\frac{\mu'}{4\pi} \frac{e^{-\mu' r}}{r^2}$$

where the origin of r is taken either at the collision point or the detector point, it is easy to sample from U_2 .

1. Choose with equal probability either S or D
2. Choose the direction toward A isotropically
3. Choose a distance r from the pdf $\mu' e^{-\mu'r}$.

This distance is either r_1 or r_2 and the remaining distance must be computed. (Note that the direction toward the intermediate point A is chosen from an isotropic distribution. Thus, if the source particle angular distribution is not isotropic, the first direction picked from S must satisfy this distribution. At the present time, ADONIS assumes isotropic angular distribution of the source particles when the flux at a point routine is used.)

The contribution to the "once more collided flux at a given detector D" from a neutron of energy E and direction $\underline{\Omega}$ entering collision at S is then given by

$$\begin{aligned} \phi(E_2^j, D) = & \{ [P(E, S)] g(\underline{\Omega} - \underline{\Omega}_1; E) e^{-\sum_i \mu(E_1, R_i) S_i} \\ & [P(E_1, A)] \mu_T [E_1, R(A)] g(\underline{\Omega}_1 - \underline{\Omega}_2; E_1) e^{-\sum_j \mu(E_2, R_j) S_j} \} \\ & / U_2(4\pi r_1^2)(4\pi r_2^2) \end{aligned} \quad (80)$$

where $\underline{\Omega}_1$, E_1 = the direction and energy after scattering at S

$\underline{\Omega}_2$, E_2 = the direction and energy after scattering at A.

$$\sum_i S_i = r_1$$

where S_i , $i = 1, 2, \dots$, denote the track lengths in the regions that the particle traverses from S to A.

$$\sum_j S_j = r_2$$

where S_j , $j = 1, 2, \dots$, denote the track lengths in regions between A and D. U_2 is computed using Eq. 78.

$[P(E,S)]$ means that a game of chance is played to find the interacting element and the type of interaction.

If the interaction at S or A is an absorption, the contribution to the once more collided flux at D is zero. If it is scattering, Eq. 80 is computed.

The contribution to the uncollided flux is finally added to obtain the total flux at detector D in each output energy interval.

$$\phi_{un}(E_2^j, D) = \frac{e^{-\sum_k \mu(E_2, R_k) S_k}}{4\pi R^2} \quad (81)$$

where

$$\sum_k S_k = R$$

where S_k , $k = 1, 2, \dots$, denote the track lengths in the regions between S and D, and E_2^j means that E_2 is in the j^{th} output energy interval.

7.4 TYPES OF ANSWERS

The ADONIS output consists of:

1. The average flux per region and per unit energy in each output energy interval, and its deviation
2. The volume V, the weight $W(E,R)$, the number of births (latent particles), deaths (by importance sampling), energy degradations (particles whose energy falls below a specified cutoff energy, if any) and absorptions in each region except the transmitting and reflecting regions
3. The number of transmitted and reflected particles

4. As an option, a total fine response and its deviations
5. As an option, coarse responses for any region
6. An interaction tape for neutron problems only
7. A transmitted particle tape.

Items 2, 3, 6, 7 have been discussed in the above subsections. This description will be restricted to items 1, 4, and 5.

7.4.1 Average Flux

There are two ways to measure the average flux, $\bar{\phi}$, in a region. The usual way is to count $m(R)$, the number of interactions in the region, and if N is the number of source particles,

$$\bar{\phi} = \frac{m(R)}{\mu_T(R) N} \quad (82)$$

This method is inefficient when R is a thin region. It is then necessary to use the other method which is called the track length method:

$$\bar{\phi} = \frac{\text{Total distance all particles traveled in } R}{(\text{Volume of } R) \times N} \quad (83)$$

It can be shown that both methods are equivalent. ADONIS computes average flux per region and per unit energy in each output energy interval using the track length method.

The source particles are considered in G equal groups of n particles each, such that $N = Gn$, each group being denoted by $g = 1, 2, \dots, G$. For most cases, 20 particles per group are taken. In any case, n must be specified in the input. This grouping is made for statistical purposes. As it will be shown, although the contribution to the average flux of all track lengths is cumulative, the contribution to the variance depends strongly on the grouping.

Let $S_g(R, E^j)$ be the sum of all track lengths of particles from the g^{th} group in region R with energy E in the j^{th} output energy interval.

The average track length per source particle per unit energy in the j^{th} interval is given by

$$\bar{S}(R, E^j) = \frac{\sum_{g=1}^G S_g(R, E^j)}{(E_j - E_{j+1}) \times G_n} \quad (84)$$

where E_j, E_{j+1} define the j^{th} energy interval.

The average flux per source particle per unit energy in the j^{th} interval in region R is given by

$$\bar{\phi}(R, E^j) = \frac{\bar{S}(R, E^j) W(E^j, R)}{V(R)} \quad (85)$$

where $V(R)$ and $W(E^j, R)$ are the volume and the weight in the j^{th} energy group of region R , respectively. If the energies are given in ev, track lengths in cm, and $V(R)$ in cm^3 , $\bar{\phi}(E^j, R)$ is obtained in number of particles per $\text{ev}\cdot\text{cm}^2\cdot\text{source particle}$.

If $V(R)$ is infinite, the ADONIS output is the product $\bar{S}(R, E^j) W(E^j, R)$.

The deviation of the average flux is obtained from

$$\sigma(R, E^j) = \frac{\bar{\phi}(E^j, G) \cdot G}{\sum_{g=1}^G S_g(R, E^j)} \sqrt{\left\langle \frac{1}{G-1} \left\{ \frac{\sum_{g=1}^G S_g^2(R, E^j)}{G} - \left[\frac{\sum_{g=1}^G S_g(R, E^j)}{G} \right]^2 \right\} \right\rangle^{1/2}} \quad (86)$$

7.4.2 Fine Response

If a functional of the type

$$\bar{f}(R) = \int_R \int_E \phi(E, \underline{X}) f(\underline{Y}, E) d\underline{X} dE \quad (87)$$

is desired (fine dose, heating ...), the ADONIS input contains a table of $f(R, E_j^G)$ at the energies, E_j^G , of the cross section used in ADONIS (81 energy mesh points). Because of core storage restrictions, a maximum of five possible distinct regions can be considered for fine response evaluation [5×81 words for $f(R, E)$ are available].

Each particle track length, $T(R, E)$, is multiplied by an interpolated value of the tabulated fine response function, $f(R, E)$, and the products are accumulated. Then the total fine response, $\bar{f}(R)$ is given by

$$\bar{f}(R) = \frac{W(R)}{G \cdot n \cdot V(R)} \sum_{g=1}^G T(R, E) f(R, E) \quad (88)$$

The deviation of the fine response is given by

$$\sigma_{\bar{f}} = \frac{W(R)}{n \cdot V(R)} \left\langle \frac{1}{G-1} \left\{ \frac{\sum_{g=1}^G T(R, E) f(R, E)}{G} - \left[\frac{\sum_{g=1}^G T(R, E) f(R, E)}{G} \right]^2 \right\} \right\rangle^{1/2} \quad (89)$$

Note that at the present time, a fine response calculation can be performed only if the region weight is not energy dependent.

7.4.3 Coarse Response

In any region, \bar{f} can be obtained by giving as input tables of $f(E_j^j, R)$, where $f(E_j^j, R)$ is piecewise constant in each output energy interval. The coarse re-

sponse is then given by

$$\bar{f} = \sum_{j=1}^{J-1} \bar{\phi}(R, E^j) f(E^j, R) (E_j - E_{j+1}) \quad (90)$$

7.5 INTERMEDIATE RESULTS

For debugging purposes and other reasons, a trace using sense switch 3 has been built into the ADONIS code. This trace permits one to follow the flight of a given number of particles. When the number of specified source particles is exhausted, the program calls the edit routine STAT.

ADONIS problems may run for long periods of time. In order to save problems so that they may be restarted, the parameters used by ADONIS have all been stored in COMMON, so that if COMMON were written on a tape, read back, and the program entered at the proper place, one could continue a problem. This coding has been placed in the ADONIS code and is activated by sense switch 1 whose function is to dump COMMON and continue the problem (the computer will print a message telling the operator to turn off sense switch 1 and will hang waiting till he does). Sense switch 1 and sense switch 6 set together will dump a problem, force an edit, and terminate. To pick up a problem that has been dumped, one places a 1 in the restart option of the first parameter card and resubmits the job as a normal ADONIS run. The code reads the dump tape and picks up from where it left off. The first parameter card must be exactly the same as the initial parameter card with the following two exceptions: (1) the last history number may be increased and (2) the restart option must be a 1. The title and the first card are all the input necessary for restarting a problem. If coarse response function data are present, these must follow the first parameter card.

7.6 ADONIS INPUT

The input required for ADONIS consists of source input, cross-section input, geometry input, and parameter input describing the particular problem of interest.

Source Input

The source input consists of a source tape containing source particles generated by programs like VANGEN or GASP. These source particles are arranged by particles blocked in groups of 100; each particle is represented by its history number, its initial position, direction, and energy, and the region of birth.

Cross-Section Input

The cross-section input consists of the desired cross sections arranged in tables so that they are accessible to the ADONIS interaction routines. These tables are placed in the COMMON portion of memory by the program DATORG. This COMMON is consistent with that used by the ADONIS interaction routines. A variable storage design has been employed so that only that storage necessary for a given problem is reserved, leaving the remaining storage available for use where necessary so that the originator may be able to expand the input where desired.

Geometry Input

Tables 1, 2, 3 described in EZGEOM are transmitted to ADONIS via COMMON.

Problem Dependent Parameter Input

The program MPINP reads in cards describing the problem.

The first parameter card contains the limits of the problem as shown below.

Entry	Type of Limit
1	The number of the first history to be treated (usually 1)
2	The number of the last history to be treated

Entry	Type of Limit
3	The number of flux bins for flux tracking
4	The number of particles per group for statistical scoring of flux
5	The total number of ordinary and nonordinary regions in the problem
6	The transmitting region number
7	The total number of distinct weights, Q
8	The number of distinct region dependent weights, q
9	The number of distinct compositions (given as input to the associated DATORG problem)
10	The number of flux-at-a-point detectors (<15), if any
11	The number of fine response functions (<6)
12	Restart option: 0 = original problem 1 = restart
13	The type of problem to be run: 0 = neutron 1 = gamma

Cards following the first parameter card contain the items listed below.

1. The cutoff energy and the thermal energy, if any. If the thermal energy entry is zero, particles slowing down below the energy cutoff are terminated and counted as degraded particles. If the thermal energy entry is nonzero, particles with energy below the energy cutoff are not terminated. They are assumed to be at thermal energy and no longer lose energy upon scattering. The cross sections used are the thermal cross sections. Absorption, reflection, transmission, or death by importance are then the only ways a history may be terminated.
2. The energy mesh points which define the output energy intervals follow. The number of entries corresponds to the number of specified energy bins plus one. The entries are in ev and in descending order.
3. The next input entries are the atomic weights per composition. This input consists of the atomic weights for each element of each specified composition, one composition per card. These cards are arranged in the

order corresponding to the DATORG input. This input is used as a check on the cross-section input read from the DATORG output. When a particle collides and the interacting element is determined, the mass of the element is taken from this list.

4. Next the weight numbers which are assigned to each region appear. Region-dependent weights and/or sets of region- and energy-dependent weights must be assigned to each region in the problem, as shown in Fig. 7. (If no importance sampling is desired, 1.0 is assigned as the weight for all regions.) For each distinct region-dependent weight and/or set of energy- and region-dependent weights, a unique number is assigned as follows: first, the numbers 1 to q , where q is the number of distinct region-dependent weights, are assigned to each of these weights; then the numbers $q+1$ to Q , where Q is the total number of distinct weights, are assigned to each of the sets of energy- and region-dependent weights. This procedure is shown on the table in Fig. 7.
The first set of cards lists, in the order of the region number (14 to a card), the weight number assigned to each region, as shown in Fig. 7. In the next set of cards the q region weights are entered in the order that the weight numbers were assigned. Then the $Q-q$ sets of energy-dependent weights are entered, each set starting a new card and in the order of their weight numbers (Fig. 7).
5. The composition number per region input follows. The input consists of the composition number from one to the number of different compositions in the problem being assigned to each region. (This is the same procedure as that described for the weight numbers.)
6. The next type of input is optional. The number of fine response functions has been specified in the first parameter card. Each response function contains a title card, a card denoting the region to which this response

Sample Problem

Region 1 $W(1) = 1.0$	Region 3 $W(3,E)$ 0.25 0.125 0.0625	Region 4 $W(4,E)$ 0.125 0.0625 0.03125	Region 5 $W(5) = 0.015625$
Region 2 $W(2, = 0.5$	Weight for each energy bin in problem	Weight for each energy bin in problem	Region 6 $W(6) = 0.015625$
Region 8 $W(8) = 0.5$			Region 7 $W(7) = 0.03125$

Table of Distinct Weights and Their Assigned Weight Numbers

Weight No.	Weight
1	1.0
2	0.5
3	0.015625
q=4	0.03125
5	(0.025, 0.125, 0.0625, 0.03125)

Total number of weights, $Q = 6$

Total number of region dependent weights, $q = 4$

Energy dependent weights for weight No. 6 (5E14.6)

0.125	0.0625	0.03125				
0.25	0.125	0.0625				
1.0	0.5	0.015625				
1	2	5	6	3	4	2

Energy dependent weights for weight No. 5 (5E14.6)

Region dependent weights in order of weight No.'s assigned (5E14.6)

Weight No. per region (1415)

Fig. 7 — Sample input cards and problem

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function applies, and the response function enumerated at each of the mesh point energies, E_j^G , that were used to create the cross-section tape.

7. The following input for flux at a point is optional. This input consists of a card containing the number of output energy bins plus one. The limits of the energy intervals are listed in ev and in descending order. A title card is next. Following the title card are cards containing the x-y-z coordinates of the detector points and the regions in which the detectors are located. The number of these cards corresponds to the number of detectors specified.
8. Finally, the coarse response function input appears. This input consists of:
 - a. A card denoting the number of coarse response functions desired (0 means no coarse response is desired)
 - b. Each response function is described in the following cards.
 - (1) A title card
 - (2) A region information card containing the number of regions for which this coarse response function applies
 - (3) The average response function for each output energy interval
 - (4) A table of the regions to which this response function applies.

7.7 ADONIS INPUT FORMS

ADONIS input forms are shown on the following pages.

ADONIS GROUP-2 INPUT

ADONIS TITLE CARD		ANY KIND OF TITLE OR PROBLEM IDENTIFICATION (CAN BE BOTH ALPHABETIC AND NUMERIC)										Card I.D. No.	
												20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 50 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	
		A,D,O,N,I,S										A,D,O,N,I,C,O,I	

ADONIS GROUP-2 INPUT (CONTINUED)

Page 2 of 12

TITLE CARD		ANY KIND OF TITLE OR PROBLEM IDENTIFICATION (CAN BE BOTH ALPHABETIC AND NUMERIC)	Card I.D. No.
Print Option	0=double space, then print 1=print on new page		
12	13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	G.P. - 2	.0 .0 .1

ENERGY INFORMATION CARD	
Cutoff energy, eV	Thermal energy cutoff: if this entry is zero, then the cutoff energy is the energy below which particles are counted as degradations. If this entry is nonzero, then the cutoff energy is the energy below which particles assume the smallest energy of the cross sections used, and this energy contains the thermal cross sections. (Particles do not degrade.)
1.0000000000000000E+000	1.0000000000000000E+000

ATOMIC WEIGHT CARD (ONE CARD PER COMPOSITION) (<20 COMPOSITION)

N. sequentially

ADONIS GROUP-2 INPUT (CONTINUED)

ENTER WEIGHT NO. CORRESPONDING TO EACH REGION. (REGIONS ARE IN ASCENDING ORDER.)
WEIGHT NUMBERS SHOULD BE IN ACCORD WITH FOLLOWING WEIGHTS.

See Fig. 7, first card

(See Fig. 7, second card)

ADONIS GROUP-2 INPUT (CONTINUED)

ENTER COMPOSITION NO. CORRESPONDING TO EACH REGION. (REGIONS ARE IN ASCENDING ORDER.)
COMPOSITION NUMBERS SHOULD BE IN ACCORD WITH DATORG INPUT.

FULL) FOR EACH (-5) REGION FOR WHICH A FINE RESPONSE FUNCTION IS REQUIRED

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... p. option: 3 double space 1 many lines.

TITLE ALPHABETICS AND NUMERICS ACCEPTABLE

FIG. 4. RESPONSIVE INFORMATION CARD

FIRST RESPONSIVE FUNCTION INFORMATION CARD		Card ID No.
Function No.	for which function is to be computed	
1	1	1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 1.10 1.11 1.12 1.13 1.14 1.15 1.16 1.17 1.18 1.19 1.20 1.21 1.22 1.23 1.24 1.25 1.26 1.27 1.28 1.29 1.30 1.31 1.32 1.33 1.34 1.35 1.36 1.37 1.38 1.39 1.40 1.41 1.42 1.43 1.44 1.45 1.46 1.47 1.48 1.49 1.50 1.51 1.52 1.53 1.54 1.55 1.56 1.57 1.58 1.59 1.500

JELLINE: RESPONSIVENESS IN COMMUNICATIVE ACTS

Card I D No

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EiRFL 111

F. R. FELLER

E.P.T.

REF ID

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REF ID

FIGURE

F.R.F. 11

F₁R₁F₁

FIR F1 L1

Number sequentially.

Each entry is given at the energy value E_G (the energies are in ascending order - see GENDA section).

If there are no coarse response functions, but external response functions are required: enter 0 in column 10

REPEAT EACH OF THE FOLLOWING FOR EACH COARSE RESPONSE FUNCTION

- Print control option: 0 = double space
1 = new page

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Number sequentially

Note: These cards must be in direct correspondence with someone who can be in the condition

ADONIS GROUP-2 INPUT (CONTINUED)

*Reg. numbers for coarse response function Be sure this corresponds with region information card

† Number sequentially

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8. DESCRIPTION OF THE UNC-SAM PROGRAM SEQUENCER (SAM)

UNC-SAM contains a program sequence* whose functions are listed below.

1. To read the program name card which appears in the input. For example, in Fig. 8, it will read first the DATORG card.
2. To check that programs that supply input have been run. In the case of DATORG, it will check that the output of GENPRO is available.
3. To read in and execute the appropriate program.
4. Upon completion of the program to check that no error has occurred. In the event of an error, UNC-SAM will bypass all subsequent programs which require the output of this program.
5. To read the next program name card and to repeat the procedure from item 2.

When SAM reads an "END" as a program name card, the program sequence is terminated. SAM is the main program on an overlay tape (logical tape 3) containing the DATORG, EZGEOM, VANGEN, GASP, and ADONIS programs.

Input* required for SAM are the numbers 0, 1, or 2 corresponding to each of the programs on the overlay tape.

0 means the corresponding program will not be run in this sequence.

1 means the corresponding program will be run.

*The description of the proper program input appears in the input section.

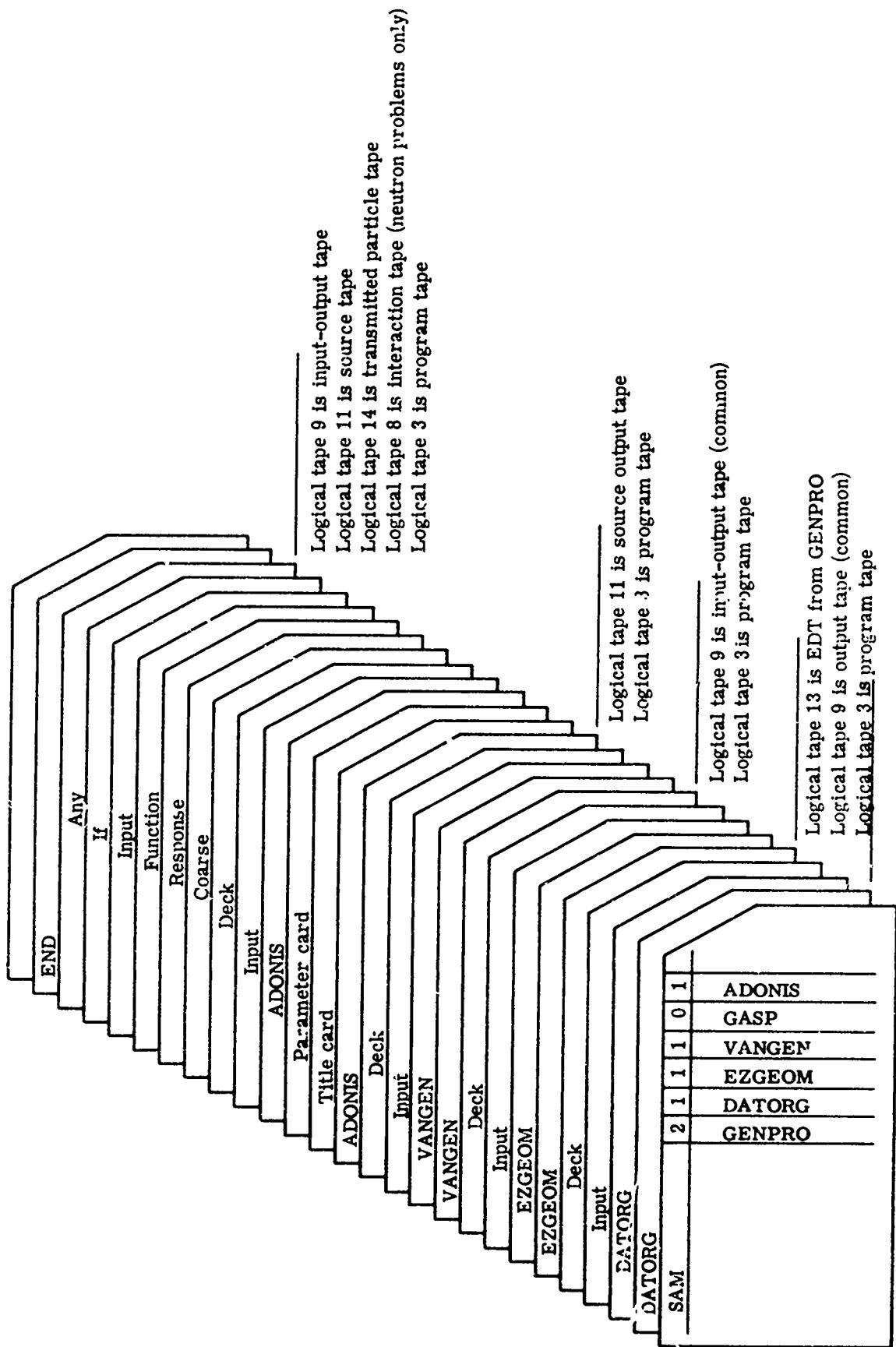


Fig. 8 — Input sequence and tape assignment for running DATORG,
EZGEOM, VANGEN, and ADONIS

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2 means the corresponding program has been run, and that the output is available for a program that will be run in this sequence.

The GENDA and GENPRO programs that supply the Element Data Tapes (i.e., the cross-section library) are separate. The Element Data Tape (output from GENPRO) is required to run DATORG. Consequently, the numbers 0 or 2 only apply as an entry in the SAM input for the program GENPRO.

A program in the sequence may appear in any order, provided all the programs that supply input to it have previously been run.

The input required for each program is preceded by a program name card.

The storage has been arranged so that all data that are problem-dependent, or are necessary for restarting a problem from a previous dump, appear in the COMMON portion of core. With this arrangement one can dump only the COMMON portion of the core on tape and be able to restart an ADONIS problem (Fig. 9). The COMMON storage tape (logical 9) must be present at all times when UNC-SAM is being used.

The program DATORG requires as input a tape containing the library of cross sections (neutron or gamma depending upon the problem specified) and composition input cards.

To signify that the cross-section tape (logical tape 13) is available, a 2 is placed in the SAM input card corresponding to the GENPRO program. To signify that DATORG is to be run, a 1 is placed in the DATORG position of the SAM card. The cross-section output of a successfully completed DATORG problem is placed on the COMMON storage tape (logical tape 9).

The COMMON storage tape (logical tape 9) is required by the program EZGEOM so that the output of a successful run may be added (if DATORG has been run pre-

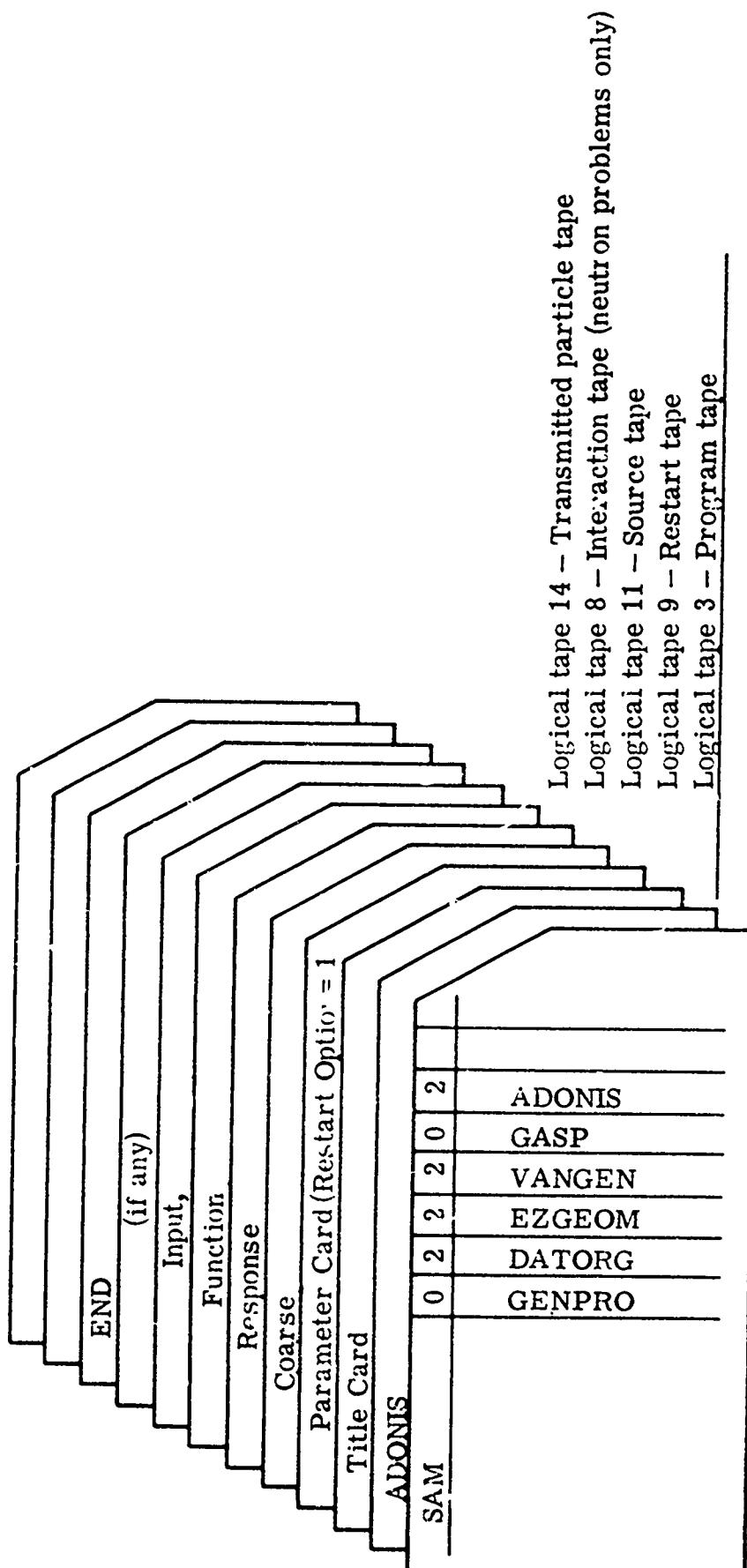


Fig. 9 — Job sequence and tape assignment for restarting an incomplete ADONIS problem

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viously), or initialized (if DATORG has not been run previously). Geometry card input data are also required to run EZGEOM (see Section 6).

The program VANGEN requires logical tape 11 as an output tape (source tape), and card input data (defining the source distribution) (see Section 5.6.1).

The program GASP requires that logical tape 11 be assigned as output and logical tape 8 from a previously run primary problem be assigned as input. Also, card input data are required (see Section 5.6.2).

The program ADONIS requires a source tape (logical tape 11) and the COMMON storage tape (logical tape 9) as input, a transmitted particle tape (logical tape 14) and an interaction tape (logical tape 8 for neutron problems only) as output.

Card input data are also required (see Section 7).

An array called TAB 3, dimensioned for 15,000 words, has been set aside to store the geometry, cross section, and statistical scoring arrays for each region (births, deaths, absorptions, degradations, sum of track-lengths for each energy bin in each region, the cumulative flux, and the cumulative square flux, the weights and composition numbers).

This array is arranged in the following manner:

Type of Data	Number of Computer Words Used
1. Geometry data	Problem dependent: (number, E, is printed when EZGEOM is run)
2. Cross-section data	Same as entry 1: D is printed (DATORG)
3. Output flux energy bin limits	J (number of energy bins) + 1
4. Weight numbers (for each region)	I (number of regions)
5. Region-dependent weights	NRDW (number of region-dependent weights)

Type of Data	Number of Computer Words Used
6. Energy-dependent weights	(IDWT-NRDW)J (IDWT = total number of distinct weights)
7. Composition per region	I
8. Absorption per region	I
9. Deaths per region	I
10. Degradations per region	I
11. Births per region	I
12. Abscrption per element per region	5·I
13. Cumulative track-length in each region and energy group	J·I
14. Cumulative track-lengths	J·I
15. Cumulative square track-lengths	J·I

The use of variable dimensioning allows for an interplay of energy bins, regions, cross-section data, and total geometry data. As long as the total number of words does not exceed 15,000, one may run an ADONIS problem.

$$D + E + 11I + 3J \times I + J + 1 + NRDW + J(IDWT - NF.DW) \leq 15,000$$

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SAM CONTROL CARD

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